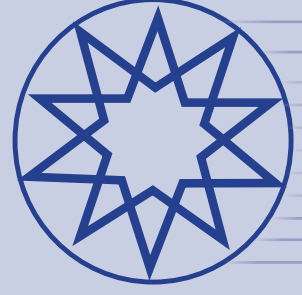


ISSN 2636-8498



Environmental Research & Technology

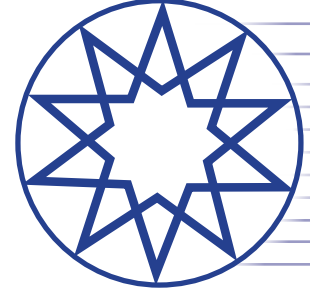
Year 2024
Volume 7
Number 1

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Volume 7 Number 1 Year 2024



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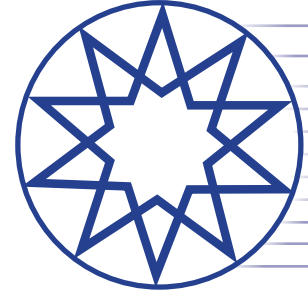
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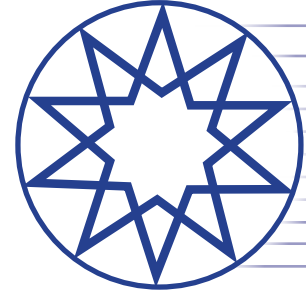
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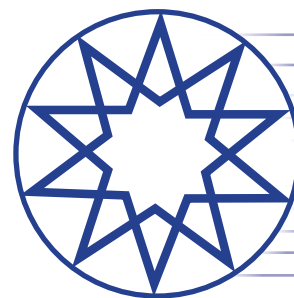
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Environmental Research and Technology
<https://ert.yildiz.edu.tr> - <https://dergipark.org.tr/tr/pub/ert>
DOI: <https://10.35208/ert.1447642>

**Environmental
Research & Technology**

Editorial

Celebrating a new milestone for environmental research and technology

Ahmet DEMİR¹, Mehmet Sinan BİLGİLİ¹

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ARTICLE INFO

Article history

Received: 05 March 2024

Accepted: 12 March 2024

Leading the launch of a new journal as Editors-in-Chief has been a captivating journey filled with triumphs and challenges. In the beginning of 2017, we commenced our efforts on the inaugural issue of the Environmental Research and Technology. Since our inception in 2018, our journal has been dedicated to fostering cutting-edge research in environmental science and technology, striving to address the critical challenges facing our planet. Today, as we stand on the threshold of another year of scholarly exploration and dissemination, it is an opportune moment to reflect on our accomplishments, express our appreciation, and outline our vision for the future. As we commence the new volume of Environmental Research and Technology Journal in the year 2024, it is with great pleasure and a sense of profound gratitude that we address you.

First and foremost, we are thrilled to announce that Environmental Research and Technology has achieved significant milestones in terms of scholarly recognition and dissemination. We are delighted to share that we are now indexed in Scopus, a testament to the quality and impact of the research published within our pages. This achievement underscores our commitment to fostering rigorous scholarship and contributing to the advancement of environmental science and technology on a global scale. It also opens new avenues for collaboration, visibility, and engagement within the academic community and beyond.

As we reach this milestone, we are filled with gratitude for the unwavering support of our authors, reviewers, and editorial board members. It is their dedication and com-

mitment that have propelled the journal to new heights, making it a beacon for scholarly excellence in the field of environmental studies.

Foremost, we extend our heartfelt gratitude to the authors whose insightful research and dedication to scientific inquiry form the backbone of our journal. Your commitment to advancing knowledge and addressing pressing environmental challenges is truly commendable, and we are privileged to serve as a platform for showcasing your work.

We also wish to express our deepest appreciation to the reviewers who generously share their expertise and insights to ensure the quality and rigor of the manuscripts we publish in Environmental Research and Technology. Your invaluable feedback and constructive criticism are instrumental in maintaining the high standards of Environmental Research and Technology.

Additionally, we extend our gratitude to the members of our esteemed editorial board for their guidance, wisdom, and unwavering commitment to excellence. Your leadership and vision continue to shape the direction of Environmental Research and Technology, guiding us towards greater achievements, and we are honored to collaborate with such distinguished colleagues.

As we embark on this new volume, we believe that Environmental Research and Technology will be marked by continued innovation, collaboration, and impactful research. Our journal will continue its mission to disseminate innovative

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Published by Yıldız Technical University Press, İstanbul, Türkiye

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research, facilitate interdisciplinary dialogue, and contribute to sustainable solutions for the myriad environmental challenges facing our planet. In the coming year, we will continue to uphold the highest standards of scientific integrity, promote diversity in our author and readership, and seek new ways to collaborate and exchange knowledge. Together we will try to solve the pressing environmental problems of our age and pave the way for a sustainable future.

In closing, we would like to invite you to join us in our work to advance Environmental Research and Technology and invite scholars and researchers who are working on any topic of environmental science to submit their papers to the journal.

USE OF AI FOR WRITING ASSISTANCE

Not declared.



Research Article

A comparative study on the selection of the most suitable route for the collection and transportation of municipal solid waste

Abdullah İzzeddin KARABULUT¹, Benan YAZICI KARABULUT², Perihan DERİN¹,
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ARTICLE INFO

Article history

Received: 30 January 2023

Revised: 21 September 2023

Accepted: 10 October 2023

Key words:

Landfill siting; Municipal solid waste management; Route optimization; GIS

ABSTRACT

Worldwide, approximately US\$410 billion is spent annually on the management of four billion tons of domestic solid waste (MSW). The transportation cost alone accounts for more than 50% of the total expenditure on solid waste management. This cost constitutes approximately 85% of the collection and transportation cost. 54.4% of environmental protection expenditures cover waste services. The population of the Barış neighborhood in the Kayapınar district of Diyarbakır, which is the subject of this study, is 23 581 according to the 2020 TÜİK data. The average amount of waste produced per person in a month is 7.6 kg/person. In the results of these statistics, it has been seen that the investment costs in the transportation of wastes are increasing day by day. In this study, the performance of ant colony and genetic algorithms, which are among the artificial intelligence techniques, and route optimization using GIS (geographic information system) software were tried to be achieved to solve the GSP (traveling salesman problem), which is included in the route planning problems. The results of the study showed that savings were achieved with an improvement of 15.1576% in GIS, 29.8104% in GA (Genetic algorithm) and 40.5171% in ACS (Ant Colony System) compared to real life. As a result of the application, it has been observed that the ant colony algorithm is superior to the Genetic algorithm and GIS, as it draws a shorter route in terms of distance and obtains a better result in terms of improvement rate.

Cite this article as: Karabulut Aİ, Yazıcı Karabulut B, Derin P, Yeşilnacar Mİ, Pamukçu H. A comparative study on the selection of the most suitable route for the collection and transportation of municipal solid waste. Environ Res Tec 2024;7(1)3–12.

INTRODUCTION

Solid waste is one of the important causes of the environmental crisis, which negatively affects human health all over the world and is rapidly approaching a disaster level that will directly threaten human life. As with all other environmental problems, the increase in solid waste produc-

tion, which goes in parallel with the increasing population and increasing consumption, has become a focus of great concern. Additionally, problem of global warming has become a major problem that the international community must face in this century. The IPCC's (Intergovernmental Panel on Climate Change) report stated that development based largely on fossil fuel energies will increase global

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average temperatures by about 4.5 °C in the 21st century. Therefore, good management of these processes is of great importance in terms of cost, environment and time. Otherwise, significant problems arise in terms of excessive fuel consumption, waste of time, depreciation expense, environment and public health [1]. In this study, optimization methods in the literature are examined in order to develop an optimal route plan for solid waste collection and transportation. Waste management has become an important issue in many developing countries as it poses significant risks to the environment and public health. Municipal solid waste generation has been increasing steadily over the last decade. In 2016, it was reported that 2.01 billion tons of municipal solid waste was generated worldwide. This figure is expected to increase to 3.4 billion tons by 2050 [2]. Even a small improvement in waste collection will result in significant cost savings, as MSW collection and handling often make up the bulk of waste management budgets [3]. The amount of waste often generated in urban areas is not known exactly. Optimizing the collection and transport of MSW contributes significantly to waste management system design [4]. In general, different sources of waste are unevenly distributed in urban areas. This situation increases waste collection and transportation costs [4]. Therefore, managers and decision makers are interested in dealing with the lowest possible cost [5].

Therefore, there is a need for an optimization system that will consider the diversity of the waste generated and take into account the costs [5]. Recently, many models have been proposed to optimize collection and transport over the entire garbage truck network. Geographic Information System (GIS) is used in some of these proposed models. GIS is a suitable tool for such studies as it can store, retrieve, analyze and apply large amounts of data, and visualize response time and output [6]. Various algorithms have been investigated for optimization problems in waste management. The reason for this diversity is that the vast majority of routing algorithms involve the use of heuristics. Heuristic algorithms are temporary, trial and error methods that do not guarantee finding the optimum solution but are designed to find near-optimal solutions in a fraction of the time required by optimal methods [7].

Optimal routing in solid waste collection includes planning and defining routes for the passage of trucks during the collection process. Failure to apply scientific or technological interventions in the selection of the optimal route causes the take distance of waste collection trucks to prolong the distance and increase the collection cost [8]. Studies in the literature have explored the solid waste collection problem in terms of optimization using mathematical programming and GIS-based approaches to achieve resource conservation and environmental protection [9]. The objective of vehicle routing is to minimize time, cost, and distance, given some relevant parameters [10, 11]. A metaheuristic approach methodology using the Ant Colony Optimization (ACO) algorithm was employed to find optimal routes with the minimum total

distance [12]. The ACO algorithm is expected to provide faster computation times for solving this problem, while ensuring that the resulting routes have the minimum total distance. Studies in routing of solid waste collection trucks therefore consider the importance of path constraints [13]. There are many studies that are similar to the subject of the study and conducted in previous years. In a study conducted ACS (Ant Colony System) was used in order to solve the road problem in the collection and transportation of wastes and to save time, and it was seen that efficient results were obtained [14]. In another study conducted it was demonstrated that high efficiency was obtained from this method by working with the Ant Colony System, which is recommended for the collection of household waste with minimal cost expenditure [15]. Conducted an optimization study using ArcGIS application in Chennai, one of the major metropolitan cities in southeast India [16]. After developing a spatial database for the whole of Chennai with 200 nodes, 13 solid waste transfer stations were identified through optimization studies using ArcGIS. This optimization process has reduced the distance traveled by 9.93%. Yetiş [17] used the Geographical Information System to calculate the groundwater salinity in the Şanlıurfa Balıklıgöl Basin and created the areal distribution maps of the study region. As a result of the study, it was observed that the sampling point was found more easily and most importantly, time was saved with the spatial mapping of GIS.

In their study, presented a hybrid algorithm consisting of a combination of GIS and genetic algorithm to reduce route length, travel time and fuel consumption [18]. Proposed a mathematical model for solving the municipal waste collection problem in order to reduce the total cost and emissions of waste collection and transportation route. They argued that the proposed model is effective in adjusting the waste collection process over time and reducing the emissions of environmental pollutants [19].

In their study, aims to improve the effectiveness of Intervention Units for Social Events (IUES) by providing decision support for efficient re-deployment to district stations. Criticality values from Erzurum province experience are used to develop a mathematical model. Optimal solutions are presented, achieving a 22% improvement in event coverage rate with three unit deployments. Expert evaluations find the results reasonable [20]. In their study, The study aims to determine the most cost-effective, safe, and uninterrupted route for hazardous materials transportation, considering the increasing industrialization. It involves face-to-face meetings with managers of a company transporting hazardous materials between Gaziantep and Erzurum provinces, using the SMAA-2 method to manage risks involved in hazardous materials transportation. This approach ensures safety and uninterrupted operations [21]. In their study, investigates the strategic-level ammunition distribution network design problem (ADNDP) for military units, focusing on determining depot locations and service assignments. The



Figure 1. Location map of study area.

methodology uses multi-objective mathematical modeling, Analytic Hierarchy Process (AHP), TOPSIS, and GIS to minimize transportation costs and risk scores. The study has applied the methodology to design and evaluate a real ammunition distribution network, using the weighted-sum method to find non-dominated solutions and discussing tradeoffs with experts. The paper presents the proposed methodology, findings, and insights [22]. In their study, focuses on the Anti-Tank Guided Missiles (ATGMs) selection problem, a strategic decision problem. The methodology uses simulation data from hundreds of scenarios to determine the best anti-tank weapon system for combat scenarios with high uncertainty. The methodology consists of four phases and 15 steps, using Fuzzy Shannon's Entropy and Fuzzy CoCoSo with Bonferroni methods. The methodology combines technical data from weapon systems and JCATS simulation tool, providing more precise criteria for combat environments. The sensitivity analysis confirms the methodology's stability, robustness, and practicality [23].

In this study, the existing solid waste collection route belonging to the Barış neighborhood of the Kayapınar district of Diyarbakır province was excavated and examined. In order to minimize the costs, Genetic Algorithm and Ant Colony method and Network Analysis method were also used to calculate the route optimization. The problem covered in the study was calculated using the Python programming language with Genetic Algorithm and Ant Colony optimization methods. In addition, a suitable route was created by using Network Analysis, which is one of the GIS analyzes. All the results obtained were compared with the existing solid waste collection route of the municipality. In this study, it is seen that significant environmental and economic gains can be achieved with different algorithms used in the route optimization process.

MATERIALS AND METHODS

Kayapınar district, which is one of the four central districts in Diyarbakır province, was chosen for route optimization. The population of Diyarbakır has increased compared to the previous year and is 1,783,431 people according to 2020 TUIK data. The area of the province is 15,168 km² and there are 118 people per km² in the province. Kayapınar, one of the central districts, has a surface area of 438 km² and is the most populous district in the province with a population of 400,905 people according to TUIK 2020 data [24]. Barış neighborhood, which is the study area, covers an area of 303.85 hectares (Fig. 1).

Barış neighborhood is a settlement where people with different socioeconomic characteristics live together, showing an example of both regular and unplanned urbanization. There are various structures within the boundaries of the neighborhood: community health center, various schools, mosque, TEİAŞ, playgrounds, health centers. In the neighborhood, wastes are collected in metal solid waste containers of 600–800 liters, located in front of apartments, parks and schools.

Solid waste is collected by 27 solid waste collection vehicles, 11 in the morning and 16 in the evening, across the Kayapınar district. While the capacity of 1 solid waste truck is approximately 5.5 to 6 tons, 162 tons of waste is collected daily in the district. An average of 16 tons of waste is collected in a week, this amount is 23 tons on Monday, 12/13 tons on Sunday and 16 tons on the remaining days. Approximately 64 tons of waste is collected monthly [25]. In Barış neighborhood, solid waste is collected by a vehicle between 06:00 and 12:00 in the morning. A fruit and vegetable market are set up in the neighborhood 2 days a week, and the vehicle collects about 8.25/9 tons of waste in 1.5 trips, collecting half an extra solid waste on those days. The wastes

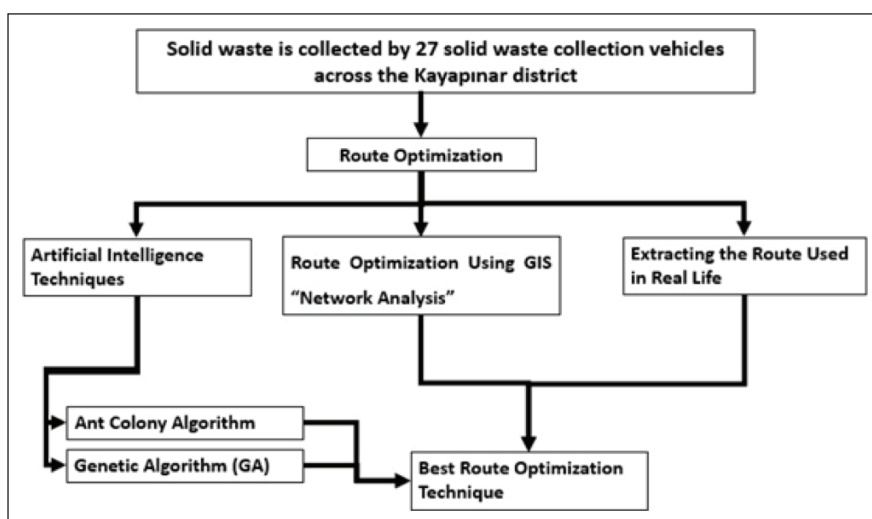


Figure 2. The block diagram of the procedure.

accumulated in the solid waste containers are collected daily by rear-loading, hydraulic compression vehicles belonging to Kayapınar Municipality.

Data Collection

Various field trips were conducted initially to determine the route of the study area and the locations of waste containers along this route. In addition, discussions were held with municipal vehicle operators to gain insight into the technical and logistical aspects. The route map of the study area was obtained from the Department of Public Works. To monitor the garbage trucks and determine the working area, the Mobilize tracking system device was utilized. By examining the routes taken by the tracking device, the coordinate data of solid waste container points were identified, and the locations of these container points were transferred to Google Earth Pro. The transferred container point data in KMZ format was then imported into Esri ArcGIS software. The block diagram of the procedure is given in Figure 2.

Bariş neighborhood has a population of 23,581 according to 2020 TÜİK data. The average amount of waste produced per person in a month is 7.6 kg/person [24]. The maximum slope of the elevation profile of Bariş neighborhood, which is one of the neighborhoods where the population with different socioeconomic characteristics is densely populated, is 14.1% and has an average slope of 2%. According to the Highways Geometric Standards, the topographic structure of Bariş neighborhood is inclined. The coordinate data of the solid waste container points were determined by checking the routes that the tracking device passed, and the locations of these container points were transferred to Google Earth Pro.

In this study, mainly the Genetic Algorithm method is used for the solution of the route optimization problem, and calculations are also made with the Ant Colony method. Using the Python programming language, Genetic Algorithm and Ant Colony optimization methods were used to calculate the shortest distances between the solid waste

container points and the result was also obtained using GIS. By comparing the results obtained, the method that gives the most appropriate route has been adopted [26].

For the GIS solution, ArcMap module, which operates based on the Dijkstra algorithm and the method of finding the shortest path, was used and the studies were carried out with the network analyst tool of this module. Creating a single or multimodal network dataset with the network analysis tool, determining the best route using a network dataset, creating a model for route analysis, transporting several orders with a fleet of vehicles, performing network analysis using traffic data, allocating the most appropriate location, etc. analysis can be done [27].

Genetic Algorithm (GA)

Genetic algorithms (GA)s can be defined as a method in which the evolutionary event is coded in the computer environment to find answers to some problems that are difficult to solve with traditional methods and an attempt is made to search for optimal or near-optimal results by using this evolutionary process. In this context, the genetic algorithm is a metaheuristic search method based on the encoding of parameters that searches randomly and tries to find a solution [28].

Instead of a single result for the problem tried to be solved in the genetic algorithm, a set of results is created in which the most appropriate result will be evaluated. The result obtained because of the calculations made in the genetic algorithm creates the possibility of being selected, but it cannot guarantee being selected. The selection to be made is random like the initial population created at the beginning, and the fitness value of the solutions shows the determination of the solution candidates [29].

GA is a heuristic screening method developed by being inspired by the change processes in nature. It is a robust and flexible approach in general and can be used to solve many problems that have both discrete and continuous character. The general solution methods group, which includes

genetic algorithms, is called evolutionary algorithms, and essentially evolutionary algorithms are a sub-branch of artificial intelligence. On a theoretical basis, it can be said that the origin of evolutionary algorithms dates to the 1950s. In particular, Turing's work titled "The Calculator and Intelligence" contains many concepts that form the basis of evolutionary algorithms [30].

Ant Colony Algorithm

In the calculation of the ant colony algorithm, it is aimed to find the shortest path inspired by the pheromone secreted by the ants along the route to find food and then return to their nests [31]. In history, Dorigo applied the algorithms created by the behavior of ants, namely the pheromone ratios they secreted, to the traveling salesman problem for the first time and obtained positive results. The positive result obtained from the algorithm has also set an example for future generations and has been used in many route problems [32].

In environmental modeling, there has been increased interest in the design of optimization models and meta-heuristic algorithms to shorten the travel routes of solid waste collection vehicles [33]. The Ant Colony Optimization (ACO) algorithm was inspired by the observation of swarm colonies and especially ants [7]. Amal [33] proposes a new Spatial Geographic Information System (GIS) based Genetic Algorithm to optimize the solid waste collection route. The algorithm proposed as SGA is a modified version of the original Dijkstra algorithm in GIS to generate optimal solutions for vehicles.

The basic logic in the ant colony algorithm is the behavior of ants while searching for food. This behavior was also measured by the pheromone they left in parallel with the probability of finding food on the route they passed. First of all, ants head towards the points where the food is found randomly. Since they secrete the smell, they call pheromone while passing there, other ants that pass through the same route head there, depending on the rate of finding food. In other words, the pheromone left by the ants passing through the route shows parallelism with the ratio of the food available at that point. The basic relationship between these pheromone traces and ants enables the ants to return to their nests where they left while searching for food. This characteristic feature in real ants has been used in artificial ant colonies to solve integrated optimization problems [34].

The first thing to do when starting the calculations with the ant colony algorithm is to determine how many ants will be used. Afterwards, each ant is randomly placed on a point, and thus, all available points are visited one by one, and the ants complete the tour. The representation of these process steps in mathematical language is given in equation 1 [34].

$$P_{i,j}^{\ell} = \frac{[\tau_{ij}]^{\alpha} [\eta_{ij}]^{\beta}}{\sum_{l \in N_i^{\ell}} [\tau_{il}]^{\alpha} [\eta_{il}]^{\beta}}, \text{ if } J \in N_i^{\ell} \quad (1)$$

Here;

P_{ij}^{ℓ} : Probability of the ant going from point i to point j

τ_{ij} : Pheromone value in the middle of i and j points

η_{ij} : Heuristic value between points i and j

α : Pheromone criterion

β : Intuitive criterion

N : Dots part

Network Analysis tool in GIS

It covers the processes of transferring all kinds of data belonging to the earth to the computer environment by establishing relations with the space and storing these data by means of special programs used, classification, comparison with each other, analysis, updating and visualization as maps, graphics, and tables as desired. As such, GIS is not just transferring and storing various data to the computer environment. The most important feature that distinguishes GIS from other database systems is that it stores all data depending on the place they belong to on earth and allows a wide variety of spatial associations, that is, various analyzes between them [35].

GIS, which started to develop in Türkiye recently, especially after the 1990s, has now been widely used in many different sectors. When we look briefly in which areas GIS is used, in socioeconomic areas, health, local government, transportation planning, service and city management applications. In defense; target area identification, tactical support, mobile command modelling, smart data integration, in business life; market sharing analysis, insurance, fleet management, target marketing, positioning of sales areas, infrastructure; network management, service provision, communication, emergency response, environmental management; It is seen that it is used effectively in site selections, EIA studies, pollution controls, disaster management and resource management.

GIS technology has been widely adopted in waste management, particularly in the planning process, due to its ability to effectively digitize spatial feature data, including the objects and their attributes with geographic accuracy. By incorporating spatial feature data, GIS technology enables efficient management and analysis of waste-related information. This includes mapping waste collection points, tracking routes, optimizing collection schedules, analyzing waste generation patterns, and identifying suitable locations for waste facilities. The extensive use of GIS technology in waste management has significantly improved the planning process, allowing for better decision-making and enhanced operational efficiency in the industry. GIS technology has gained widespread use in waste management, particularly in the planning process, due to its ability to effectively digitize spatial feature data, including the object and its attributes with geographic accuracy. By incorporating spatial feature data, GIS technology enables comprehensive utilization in waste management, particularly in the planning phase [36]. In this context, ArcGIS, with its network analysis extension, allows users to dynamically model realistic network conditions, including turn restrictions, speed limits, and traffic

conditions. Network analysis in ArcGIS not only examines the closest facility within a digitized connected line network but also provides the ability to model specific network attributes based on inputs such as traversal distance, travel time and cost, barriers, vehicle restrictions, and more [37].

Municipalities have limited budgets for basic sanitation services, which is why technological strategies and trained human resources are necessary for improved municipal solid waste management. From a technical perspective, GIS provide a powerful tool to model and optimize service routes where a better scenario can be proposed. GIS offers up-to-date services in terms of modeling and optimizing service routes for improved municipal solid waste management [38]. In addition to the ability to store verbal information of spatial data in an integrated way in the database, GIS also has the feature of querying and processing these data with the help of programming languages and visualizing the analysis results. For this reason, it provides visualization and more appropriate analysis of classical database operations such as data storage, querying and statistical analysis.

RESULTS AND DISCUSSION

Performing Route Optimization with Genetic Algorithm

There are 105 solid waste container points belonging to Barış neighborhood. The coordinates of these container points were obtained from the Google Earth Pro application and a dataset was created with this information. The created coordinate information was transferred to the working environment using the “Pandas” library. The data set was obtained by labeling the coordinate information of 105 solid waste containers. The distance information obtained by calculating the Euclidean distance between the tagged coordinates was used in the genetic algorithm. The formula used to calculate the distance is as follows:

$$d = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} \quad (2)$$

Using the distances obtained by the formula, the following steps were used to determine the best route between the container points.

1. Creation of the starting route; At this stage, a random route was created between 105 coordinates.
2. Calculation of the total length of the created route: Calculation of the distance between the points of the route created with the Euclidean distance shared in the formula.
3. Performing crossover between points: Creating a new route by performing crossover between selected points.
4. Mutation: Applying a mutation between the new route created according to the mutation probability.
5. Continuing the cycle by returning to the second step for the specified number of steps.

For population formation, which is one of the stages of the genetic algorithm, the data entry of 105 containers was written in accordance with the python programming language. When it comes to the final stage in the calculation of the Genetic Algorithm, routes were created according to

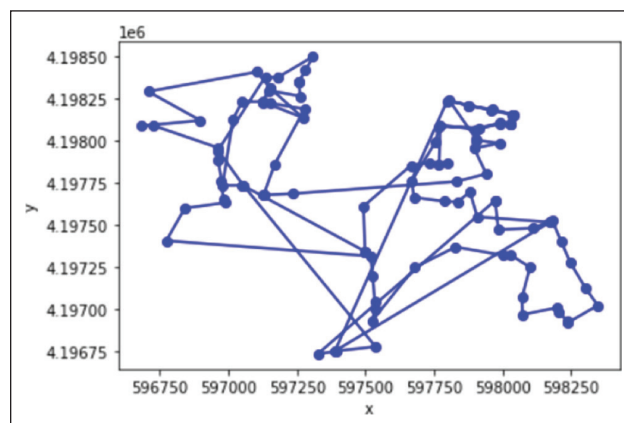


Figure 3. 1000. The population-generated route.

Table 1. The best distance values obtained according to the number of generations

Population	Distance (m)
1. Population	75965.44
100. Population	59833.45
1000. Population	18910.63

the number of generations and distance calculations were made with this route. The distance after the 1000th population was 18910.63 meters (18.9106 km) (Figure 3, Table 1). The results obtained in Table 1 are shown in meters.

Performing Route Optimization with Ant Colony

There are some parameters that need to be determined when calculating the Ant Colony Algorithm. What these parameters are can be explained step by step as follows:

- Number of Steps: Indicates how many steps the optimization process will take.
- Number of Ants: It refers to the total number of ants in the colony.
- Alpha Value: Indicates the importance of the pheromone value between points.
- Beta Value: Indicates the importance value of the distance between the points.
- Pheromone Evaporation Value: Indicates the pheromone evaporation rate between points after each step.

In accordance with the parameters mentioned above, the values of the CCA calculated in the ‘python’ computer programming language are given in Table 2.

As shown in Table 2 above, ant colony algorithm parameters were determined. The following steps were taken in line with these determined parameters and optimization was carried out with the data set used in section 2.

Step 1: Ants are randomly placed on the dots.

Step 2: Each ant creates a route according to the determined alpha and beta values.

Step 3: The created route values are calculated.

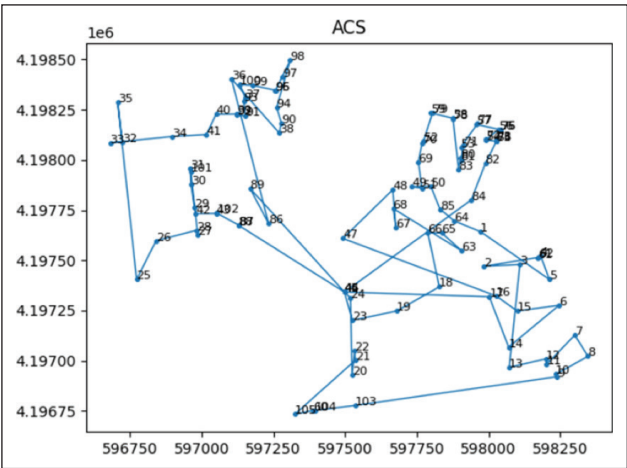


Figure 4. Ant colony algorithm optimization map.

Table 2. Ant colony algorithm parameter values

Parameter	Value
Number of steps	1000
Number of ants	150
Alpha ratio	1.0
Beta rate	3.0
Pheromone evaporation rate	1.0

- Step 4: The pheromone ratio in the route that the ants pass according to the direction they form is increased.
- Step 5: The amount of pheromone on the route is reduced according to the pheromone evaporation rate.
- Step 6: It is repeated by returning to Step 2 as many as the number of steps.

Optimization was achieved in 1000 iterations by following the specified steps, and the route obtained is shown in Figure 4. The total distance obtained according to the CCW optimization result shown in Figure 4 is 16026.21 m (16.0262 km).

Solution of Route Optimization with GIS

It is solved with the route feature of the ArcMap network analysis tool of Esri ArcGIS application. As a result of these solutions, the results of the solution of 11 problem sets are shown in Figure 5. The distance obtained for this ranking is 22.9616 km. Each result in the table; It shows the most suitable route between the vehicle starting from the first point, stopping at other destination points, and returning to the starting point again.

Extracting the Route Used in Real Life

Mobilize tracking device is placed in solid waste collection vehicles to determine the route used for the collection of household waste in Barış neighborhood. Thanks to the tracking device, the data of the application can be obtained when the solid waste collection vehicle enters and exits the neighborhood. By analyzing the data obtained at the end of the day,

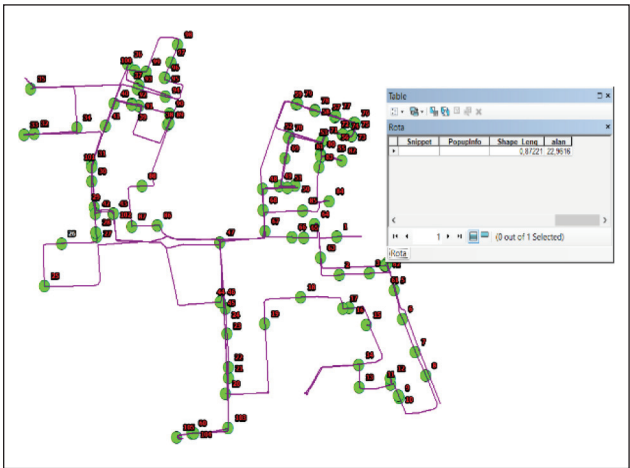


Figure 5. Network analysis optimization map.

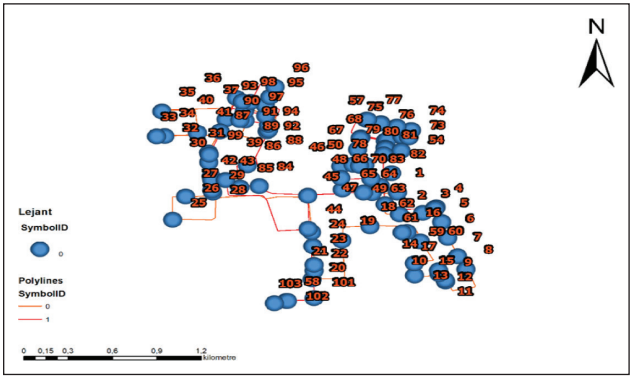


Figure 6. Route ranking used in real life.

105 container points were determined on the route of Barış neighborhood. The distances between 105 container points on this route have been calculated as 22.8488 km (Fig. 6).

CONCLUSIONS

The waste collection plays a crucial part in the waste management system because of the high cost of transportation. As a result, waste management activities are becoming more and more important. Decision-makers are now required to make educated choices due to rising costs of solid waste management, which account for a considerable share of total expenses for local administrations.

This study addresses the waste collection and transportation problem, which constitutes a significant portion of the costs of solid waste management systems. In particular, genetic algorithm, ant colony algorithm and traveling salesman problem optimization are used to generate feasible solutions to the waste collection problem involving 103 points distributed in Barış neighborhood of Kayapınar district of Diyarbakır. The results obtained with the studies carried out in this direction were compared with the real-life data.

Using real-life data for a small area and evaluating the studies on it can provide convenience. However, as the working area grows, optimization studies are carried out with the emergence of constraints such as time, traffic density, number of

vehicles and increase in the number of employees. In the study conducted for this purpose, it has been seen that GIS, GA and CCA give more advantageous results than real life data.

As a result of the study, it was seen that savings were achieved with 15.1576% improvement in GIS, 29.8104% improvement in GA (Genetic algorithm) and 40.5171% improvement in ACS (Ant Colony System) against real life data. As a result of the application, it was seen that the ant colony algorithm is superior to the Genetic algorithm and GIS because it draws a shorter route in terms of distance and achieves a better result in terms of improvement rate.

Within the scope of this study, it has been tried to optimize the route used in the collection and transportation of solid wastes with GIS, Ant Colony Algorithm and Genetic Algorithm. The results obtained with the studies carried out in this direction were compared with the real-life data.

Using real-life data for a small area and evaluating the studies on it can provide convenience. However, as the working area grows, optimization studies are carried out with the emergence of constraints such as time, traffic density, number of vehicles and increase in the number of employees. In the study conducted for this purpose, it has been seen that GIS, GA and CCA give more advantageous results than real life data.

In the process of determining the optimum route used by local governments in the collection and transportation of domestic solid waste; It has been seen by experimental studies that the use of heuristic methods has a significant share in terms of economic and environmental gains. Optimization and comparison of the traveling salesman problem with the genetic algorithm and the ant colony algorithm were used to calculate the route optimization in the collection and transportation of solid wastes. With the calculations made, it was seen that the ant colony gave a better improvement result than the genetic algorithm. A GIS solution was implemented using the network analysis tool of the ArcMap module of the Esri ArcGIS application. In large-scale study areas, GIS gives more advantageous results than real data. Likewise, it has been seen that the result obtained from ArcGIS for the study area is more advantageous than the real data. Likewise, in the neighborhood, which is the subject of the thesis, it was seen that the result obtained from ArcGIS was more advantageous than the real data. It has been determined by calculations that the efficiency obtained from algorithms used outside of GIS is much more advantageous. In the calculations made under four headings for Barış neighborhood, the most advantageous ratio was obtained with the Ant Colony Algorithm, with a distance of 16.0262 km and an improvement of 40.517%.

In this study, calculations were performed on certain criteria with different algorithms. More extensive studies can be carried out by adding criteria such as time and cost to the algorithms. As a result, in the determination of the optimum route used by local governments in the collection and transportation of domestic solid waste; It has been seen by experimental studies that the use of heuristic methods has a significant share in terms of economic and environmental gains.

In the next study plan, the problem will be done to cover the whole district and the whole province. While solving these problems, other real life constraints such as vehicle breakdown and traffic congestion will be added, and optimization solutions will be produced.

Acknowledgements

This study was financially supported by Harran University Scientific Projects Research Coordinator (HUBAP) under grant no 20150.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

REFERENCES

- [1] A. İ., Karabulut, B., Yazici-Karabulut, P. Derin, M. İ., Yesilnacar, and M. A., Çullu, "Landfill siting for municipal solid waste using remote sensing and geographic information system integrated analytic hierarchy process and simple additive weighting methods from the point of view of a fast-growing metropolitan area in GAP area of Turkey," *Environmental Science and Pollution Research*, 29, 4044–4061, 2022. [\[CrossRef\]](#)
- [2] S., Varjani, H., Shahbeig, K., Popat, Z., Patel, S., Vyas, A. V., Shah, and M., Tabatabaei, "Sustainable management of municipal solid waste through waste-to-energy technologies," *Bioresource Technology*, Vol. 355, Article 127247, 2022. [\[CrossRef\]](#)
- [3] W., Xue, K., Cao, and W. Li, "Municipal solid waste collection optimization in Singapore," *Applied Geography*, Vol. 62, pp. 182–190, 2015. [\[CrossRef\]](#)
- [4] K., Nguyen-Trong, A., Nguyen-Thi-Ngoc, D., Nguyen-Ngoc, and V., Dinh-Thi-Hai, "Optimization of municipal solid waste transportation by integrating GIS analysis, equation-based, and agent-based model," *Waste Management*, Vol. 59, pp. 14–22, 2017. [\[CrossRef\]](#)
- [5] E., Babae Tirkolaee, I., Mahdavi, M. M., Seyyed Esfahani, and G. W., Weber, "A hybrid augmented ant colony optimization for the multi-trip capacitated arc routing problem under fuzzy demands for urban solid waste management," *Waste Management and Research*, Vol. 38(2), pp. 156–172, 2020. [\[CrossRef\]](#)
- [6] A., Malakahmad, P. M., Bakri, M. R. M., Mokhtar, and N., Khalil, "Solid waste collection routes op-

- timization via GIS techniques in Ipoh city, Malaysia,” *Procedia Engineering*, Vol. 77, pp. 20–27, 2014. [CrossRef]
- [7] N. V., Karadimas, M., Kolokathi, G., Defteraiou, and V., Loumos, “Ant colony system vs ArcGIS network analyst: The case of municipal solid waste collection,” In 5th WSEAS international conference on environment, ecosystems and development (pp. 128–34), 2007. [CrossRef]
- [8] G., Tavares, Z., Zsigraiova, V., Semiao, and M. G., Carvalho, “Optimisation of MSW collection routes for minimum fuel consumption using 3DGISmodelling,” *Waste Management*, 29(3), 1176–1185, 2009. [CrossRef]
- [9] A., Sulemana, E. A., Donkor, E. K., Forkuo and S., Oduro-Kwarteng, “Optimal routing of solid waste collection trucks: A review of methods,” *Journal of Engineering*, Vol. 2018, Article 4586376, 2018. [CrossRef]
- [10] A. V., Bhambulkar and I. P., Khedikar, “Municipal solid waste (MSW) collection route for laxmi nagar by geographical information system,” *International Journal of Advanced Engineering Technology*, Vol. 2(4), pp. 48–53, 2011. [CrossRef]
- [11] C. A., Arribas, C. A., Blazquez, and A., Lamas, “Urban solid waste collection system using mathematical modelling and tools of geographic information systems,” *Waste Management & Research*, Vol. 28(4), pp. 355–363, 2010. [CrossRef]
- [12] D. H., Dayanara, N. I., Arvitrida, and N., Siswanto, “Vehicle routing problem with split service, time window and intermediate facility for municipal solid waste collection in surabaya city with ant colony optimization algorithm,” In *IOP Conference Series: Materials Science and Engineering*, Vol. 598(1), Article 012020. IOP Publishing, 2019. [CrossRef]
- [13] P., Keenan, “Modelling vehicle routing in GIS,” *Operational Research*, Vol. 8(3), pp. 201–218, 2008. [CrossRef]
- [14] J., Liu, and Y., He, “A Clustering-Based Multiple ant colony system for the waste collection vehicle routing problems,” *Fifth International Symposium on Computational Intelligence and Design*, 28–29 October, Hangzhou, China, pp.182–185, 2012. [CrossRef]
- [15] M., Reed, A., Yiannakou, and R., Evering, “An ant colony algorithm for the multi-compartment vehicle routing problem,” *Applied Soft Computing*, 15, pp. 169–176, 2014. [CrossRef]
- [16] V., Sanjevi, and P., Shahabudeen, “Optimal routing for efficient municipal solid waste transportation by using arc gis application in chennai, India,” *Department of Industrial Engineering, College of Engineering, Anna University, India. Sage Journals*, Vol. 34(1), pp. 11–21, 2016. [CrossRef]
- [17] R. A., Yetiş, “Şanlıurfa Balıklı göl havzasında yer altı suyu tuzluluğunun coğrafi bilgi sistemi kullanılarak değerlendirilmesi,” *Uluslararası Su ve Çevre Kongresi*, Mart, Bursa, pp. 1, 2018.
- [18] L., Amal, L. H., Son, and H., Chabchoub, “SGA: spatial GIS-based genetic algorithm for route optimization of municipal solid waste collection,” *Environmental Science and Pollution Research*, Vol. 25, pp. 27569–27582, 2018. [CrossRef]
- [19] J., Valizadeh, P., Mozafari, and A., Hafezalkotob, “Municipal waste management and electrical energy generation from solid waste: a mathematical programming approach,” *Journal of Modelling in Management*, Vol. 17(1), pp. 309–340, 2022. [CrossRef]
- [20] O., Demirdöğen, H., Erdal, and E., Acar, “An integrated model proposal for increasing the effectiveness of security service production: A multi-criteria maximal covering model,” *International Journal of Recent Scientific Research*, Vol. 6(6), pp. 4881–4890, 2015.
- [21] H., Erdal, “Tehlikeli madde taşımacılığı güzergâh seçimi problemi için stokastik bir risk analizi,” *Anemon Muş Alparslan Üniversitesi Sosyal Bilimler Dergisi*, Vol. 6(6), pp. 935–943, 2018. [Turkish]
- [22] İ., Akgün, and H., Erdal, “Solving an ammunition distribution network design problem using multi-objective mathematical modeling, combined AHP-TOPSIS, and GIS,” *Computers & Industrial Engineering*, Vol. 129, pp. 512–528, 2019. [CrossRef]
- [23] H., Erdal, K., Kurtay, H., Dagistanli, and A., Altuntas, “Evaluation of anti-tank guided missiles: An integrated fuzzy entropy and fuzzy cocoso multi criteria methodology using technical and simulation data” *Applied Soft Computing*, Vol. 137(C), Article 110145, 2023. [CrossRef]
- [24] TÜİK, “Turkish Statistical Institute,” <https://www.tuik.gov.tr/>. Accessed on Feb 16, 2021.
- [25] Anonymous, “Çevresel göstergeler,” <https://cevreselgostergeler.csb.gov.tr/atik-duzenli-depolama-tesis-sayisi-belediye-sayisi-hizmet-verilen-nufus-i-85750> Accessed on Feb 16, 2021.
- [26] H., Pamukçu, “Optimization of solid waste collection route: The example of Kayapinar (Diyarbakir) county,” *Harran University Graduate School of Natural and Applied Sciences*, [Unpublished Master Thesis], 2022.
- [27] O., Rızvanoğlu, S., Kaya, and M., Ulukavak, “Optimization of municipal solid waste collection and transportation routes, through linear programming and geographic information system: a case study from Şanlıurfa, Turkey,” *Environmental Monitoring and Assessment*, Vol. 192, Article 9, 2020. [CrossRef]
- [28] Ç., Elmas, “Yapay Zeka Uygulamaları,” Seçkin Yayıncılık, 2007. [Turkish]
- [29] B., Özkan, “Design and implementation of an optimization library with visual software development environment for the solution of dynamic traveling salesman problem,” *Ege University, Institute of Science and Technology*, [Unpublished Master Thesis], İzmir, 2008.
- [30] Y., Pehlivanoğlu, “Optimizasyon: temel kavramlar ve yöntemler,” Ankara, 2017.

- [31] M., Demircioğlu, "A heuristic approach to vehicle routing problem and an application," Çukurova University, Institute of Social Sciences, [Doctorial Thesis], Adana, pp. 175, 2009,
- [32] M., Dorigo, and G., Di Caro, "Ant colony optimization: a new meta-heuristic," In Proceedings of the 1999 congress on evolutionary computation-CEC99 (Cat. No. 99TH8406) (Vol. 2, pp. 1470-1477). IEEE, 1999.
- [33] L., Amal, L. H., Son and H., Chabchoub, "SGA: spatial GIS-based genetic algorithm for route optimization of municipal solid waste collection," Environmental Science and Pollution Research, Vol. 25, pp. 27569–27582, 2018. [\[CrossRef\]](#)
- [34] S., Serin, "Planning of highway routine pavement maintenance work using ant colony approaches," Süleyman Demirel University, Institute of Science and Technology, [Unpublished Master Thesis], pp. 89, 2009.
- [35] A., Demirci, and M., "Karakuyu, Afet yönetiminde coğrafi bilgi teknolojilerinin rolü," Doğu Coğrafya Dergisi, Vol. 9(12), pp. 67–100, 2004.
- [36] H., Cheniti, M., Cheniti, and K., Brahamia, "Use of GIS and Moran's I to support residential solid waste recycling in the city of Annaba, Algeria," Environmental Science and Pollution Research, Vol. 28, pp. 34027–34041, 2021. [\[CrossRef\]](#)
- [37] D., Das, A. K., Ojha, H., Kramsapi, P. P., Baruah, and M. K., Dutta, "Road network analysis of Guwahati city using GIS". SN Applied Sciences, Vol. 1, pp. 1–11, 2019. [\[CrossRef\]](#)
- [38] V., Del Carmen-Niño, R., Herrera-Navarrete, A. L., Juárez-López, M. L., Sampedro-Rosas, and M., Reyes-Umaña, "Municipal solid waste collection: challenges, strategies and perspectives in the optimization of a municipal route in a southern mexican town". Sustainability, Vol. 15(2), Article 1083, 2023. [\[CrossRef\]](#)



Research Article

Physicochemical characterization of university campus' wastewater for internal treatment system installation (Casablanca, Morocco)

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ARTICLE INFO

Article history

Received: 27 June 2023

Revised: 22 October 2023

Accepted: 13 November 2023

Key words:

Biodegradability; FSBM;
Physicochemical; Quality;
Wastewater

ABSTRACT

Today, protecting water resources and their sustainable use has become an obligation of people and organizations. Wastewater management and reclamation are the most important solutions to protect these resources. This study aims to determine the wastewater physicochemical quality of the Faculty of Sciences Ben M'Sick (FSBM) (Casablanca, Morocco) to establish the appropriate system for their treatment and internal reclamation. The results show that averages of FSBM's wastewater temperature vary between 17.64 and 19.55 °C, 7.18 and 8.18 for pH, and 2.47 and 3.98 mS.cm⁻¹ for electrical conductivity. The COD, BOD₅, and TSS average values oscillate respectively between 967.44–1.151.08 mg.L⁻¹, 70.5–119.05 mg.L⁻¹, and 223.64–1.659.74 mg.L⁻¹, and those of total phosphorus between 2 and 3.99 mg.L⁻¹. The determination of the biodegradability degree of the discharge, through the calculation of COD/BOD₅, BOD₅/COD, TSS/BOD₅, COD/TP, COD/NH₄⁺ ratios, and oxidizable matters (OM_i) reveals that the FSBM's wastewater has a heterogeneous character with a high load of oxidizable matter difficult to biodegrade. Despite its low biodegradability, the FSBM's wastewater could be treated using a biological treatment system, preceded by a physicochemical treatment to eliminate non-biodegradable chemical substances. Such a choice of wastewater treatment system requires prior experimental investigations and laboratory tests.

Cite this article as: Grimah K, Nahli A, Lazrak A, Chlaida M. Physicochemical characterization of university campus' wastewater for internal treatment system installation (Casablanca, Morocco). Environ Res Tec 2024;7(1)13–26.

INTRODUCTION

Water is an essential natural resource, and the assurance of sufficient quantity and quality of this material for each of us has become one of the significant challenges of the 21st century. Water scarcity is a real threat to many nations, and they are being made worse by population increase, excessive water resource use, and the escalating consequences of climate change. In the Mediterranean region, water resources are highly vulnerable to climate change [1], notably impacting the integrity of aquatic ecosystems and the water availability for agricultural irrigation and domestic and industrial activities [2, 3].

Morocco, known for its semi-arid Mediterranean climate, is no exception to water stress in the Middle East and North Africa (MENA) region. Indeed, the country is facing a significant water shortage due to increased water demand and reduced rainfall induced by climate change. This reduction in water resources intensely conditions the country's socioeconomic development ambition. It limits the activities of different sectors of the national economy [4, 5], which could reduce Morocco's GDP by up to 6.7 billion US dollars per year [6]. Thus, investing in water efficiency practices and developing non-conventional resources can mitigate this water stress situation.

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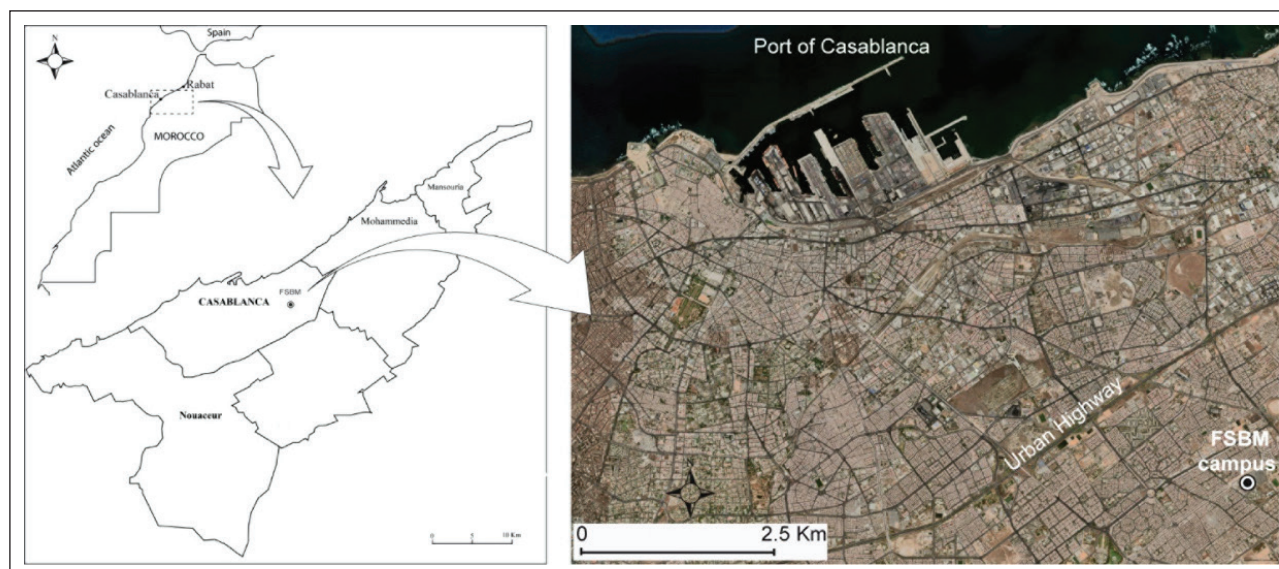


Figure 1. Geographical location of the study area (Faculty of Sciences Ben M'Sick campus).

For this purpose, Morocco adopted a National Water Strategy (NWS) in 2009 [7], which focuses on managing, preserving, and developing water resources, reducing vulnerability to water-related risks, and adaptation to climate change. In addition, the country has developed the National Strategy for Sustainable Development to 2030 (NSSD) to include all the country's development sectors and activities in sustainable exploitation and production, integrating social, economic, and environmental components [8].

This NSSD's application in the higher education sector has resulted in implementing the 2030 education and training strategy through framework law 17.51 [9]. This law stipulates that university campuses must accommodate and train students in socially, economically, and environmentally sustainable sites. Thus, university institutions must be environmentally and energetically resilient and rehabilitated to adapt to the requirements and imperatives of sustainable management of their resources (water, energy, etc.) and waste (liquid effluents, solid waste, etc.).

Thus, the treatment and reuse of wastewater (WW) is a requirement for the sustainable development of university campus activities. However, university campus teaching and research activities generate rather heterogeneous and complex wastewater [10]. Although limited in number, studies on the characterization of university campus effluents have shown that the WW produced by restrooms, dormitories, and restaurants is generally domestic and biodegradable [11–13]. However, the effluents produced by laboratories and practical rooms are heterogeneous and typically of an industrial nature and are biodegradable only to a limited extent [10–13]. This physicochemical profile makes this wastewater treatment quite difficult, to comply with the discharge standards into the city sewerage system or their reuse and recycling.

The main objective of this work is to contribute to the establishment of the Ben M'Sick Faculty of Sciences/ Hassan

II University of Casablanca (Morocco) in a sustainable water management approach and to apply a "Zero discharge" approach by installing an internal treatment and reuse system for treated wastewater. Before that, the physicochemical characteristics of these WW were assessed, including temperature "T", pH, electrical conductivity "EC", turbidity "Tur", total phosphorus "TP", orthophosphate, chemical oxygen demand "COD", biological oxygen demand in five days "BOD₅", total suspended solids "TSS", ammonium ion, nitrate, and nitrite, as well as total and calcic hardness "TH/CH", chloride, and sulfate. More precisely, it is a question of determining the WW's load in nutrients and oxidizable matters and their biodegradability degree to propose adequate treatment.

MATERIALS AND METHODS

Study Site

The Faculty of Sciences Ben M'Sick is an institution of higher education attached to the University Hassan II of Casablanca (Central West Morocco). It is built on a four (4) hectares site northeast of this city (Fig. 1), on sandy-clay soil and a groundwater table at 60–70 m depth.

The area's climate is semi-arid with temperate winters, and the institution has, in 2022, about 9,700 students and 280 teachers, researchers, and administrative staff [14]. This institution's consumption of drinking water varied globally between 12,000 and 15,000 m³ for 2019–2022. The average volume of wastewater produced by the various pedagogical and scientific activities (research laboratories and practical work rooms) in the various premises of the institution can be estimated within a range of 9,600 and 12,000 m³ year⁻¹, according to a return rate of 80% of consumption water (i.e., 12,000–15,000 m³ year⁻¹). This wastewater is evacuated through a unified network directly into the urban sewerage system of the city of Casablanca.

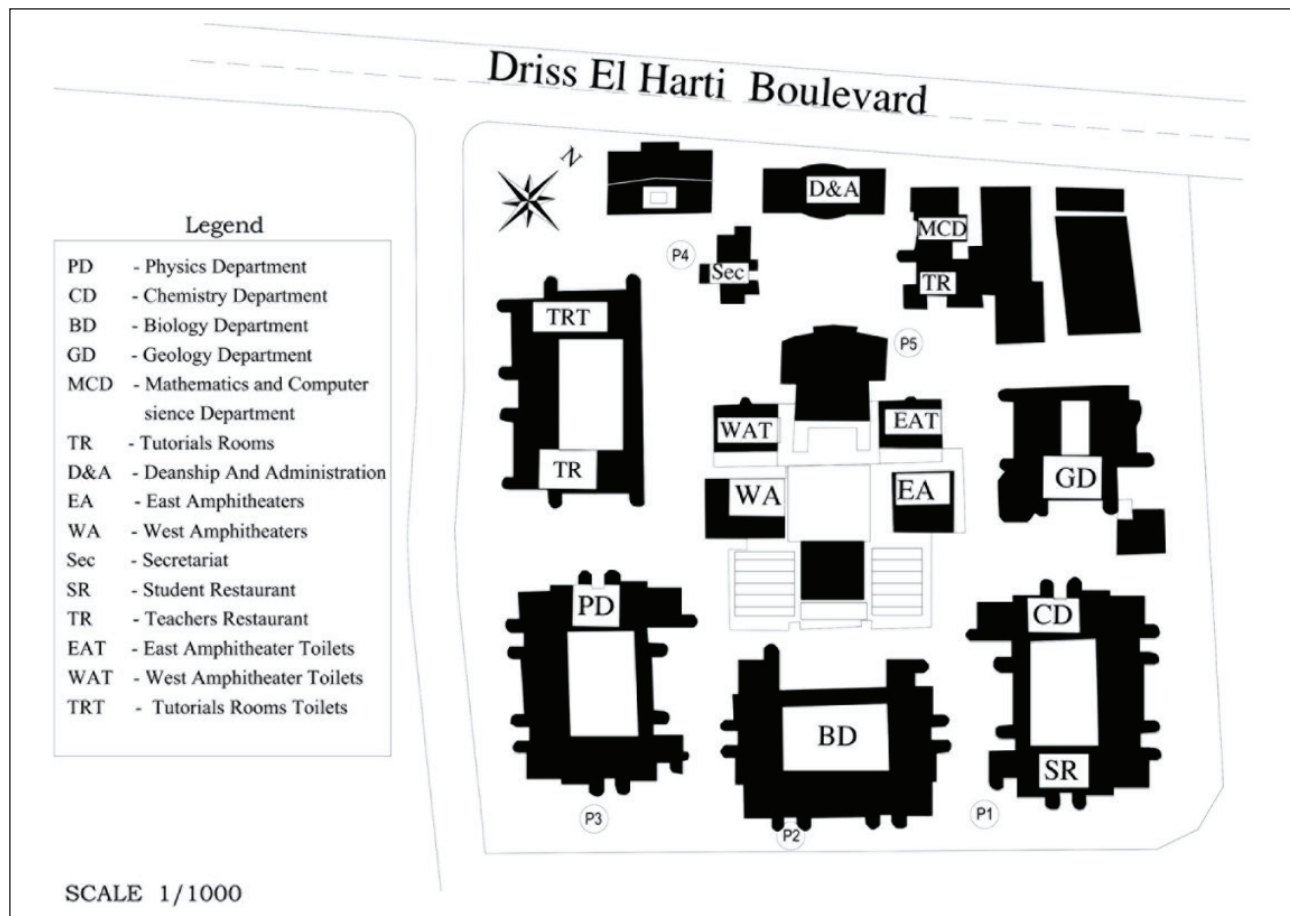


Figure 2. Location of wastewater sampling points (P1, P2, P3, P4, and P5).

Wastewater Sampling and Analysis Methods

The wastewater samples are taken weekly from November 2021 to June 2022 at five maintenance holes of the establishment's wastewater network. These sampling points, chosen according to their location and the wastewater's origin, include (Fig. 2): Point P1: Department of Chemistry and student restaurant; P2: Department of Biology; P3: Department of Physics; P4: toilets of the tutorial's rooms and "West" Amphitheaters; P5: toilets of "East" Amphitheaters and teacher's restaurant.

The wastewater, collected in rinsed 500 ml polyethylene bottles, is transported directly to the laboratory to be analyzed according to AFNOR's standardized methods [15]. In parallel, in situ temperature, pH, and electrical conductivity measurements are performed. Table 1 presents the characteristics of the equipment and the methods used for physicochemical analyses.

Based on the results of the WW analyses, pollution ratios and the oxidizable matter (OM) contents were calculated to better appreciate the nature of these effluents and guide the treatment process choice. These different ratios calculated are:

- BOD_5/COD ratio: indicates the pollution's origin of the WW and the possibilities of their treatment. It characterizes industrial pollution [16].
- COD/BOD_5 ratio: accounts for a fraction of readily biodegradable matter concerning all oxidizable matter. Bi-

ological treatment of WW can be considered if the ratio is low. Conversely, a high value of this ratio indicates that a large part of the organic matter is not biodegradable. In this case, it is preferable to consider a physicochemical treatment. This ratio can also indicate that the WW discharged is domestic if it is less than 3 [17].

- TSS/ BOD_5 ratio: provides information on the degree of sedimentation of suspended solids to the organic load of the WW. The greater the ratio, the slower TSS sedimentation.
- COD/TP (C/P) ratio: provides information on the relative mix of the effluent and the potential and effectiveness of biological phosphorus treatment [18]. The lower the C/P ratio, the greater the phosphorus removal in biological treatment systems [19].
- COD/NH_4^+ ratio (C/N): indicates the relative mix of the effluent, which influences denitrification and the advantage of having a dissociated anoxic zone in the aeration tank [18]. According to Chiu et al. [20], the C/N ratio regulates the co-occurrence of nitrification and denitrification. The greater the C/N ratio (greater than three), the more nitrogen is removed [21].
- The amount of oxidizable matter (OM) in the WW was calculated according to the equation [15]:

$$OM = \frac{(COD + 2 BOD_5)}{3} \quad (1)$$

Table 1. References of the equipment and methods used for the physicochemical analyses

Parameter	Unit	Material and method	Reference
Temperature (T)	°C	Multi parameters type VW	–
Hydrogen potential (pH)		pH meter type WTW SenTix 51	–
Electrical conductivity (EC)	mS cm ⁻¹	Multi parameters type VWR	–
Turbidity (Tur)	NTU	Turbidimeter type BANTE, TB100	–
Biochemical oxygen demand in 5 days (BOD ₅)	mg L ⁻¹	BOD-mètre type VELP SCIENTIFICA	–
Chemical oxygen demand (COD)	mg L ⁻¹	Oxidation with potassium dichromate using a COD meter type VELP SCIENTIFICA, ECO 6 Thermoreactor	NF T 90-101
Total suspended solids (TSS)	mg L ⁻¹	Filtration on a Wattman GFC filter	NF EN 872
Ammonium (NH ₄ ⁺)	mg L ⁻¹	Indophenol blue spectrophotometric method NFT 90-015	NFT 90-015
Nitrite (NO ₂ ⁻)	mg L ⁻¹	Sulfanilamide diazotization in acid medium	NFT 90-013
Nitrate (NO ₃ ⁻)	mg L ⁻¹	Sodium salicylate method	NF T 90-012
Total phosphorus (TP)	mg L ⁻¹	Oxidation with peroxodisulfate	NF EN 1189
Orthophosphate (PO ₄ ²⁻)	mg L ⁻¹	Reduction with ascorbic acid	NF EN 1189
Calcium Hardness (CH)	mmol L ⁻¹	The method by complexometry (EDTA)	NF T90-016
Total Hardness (TH)	mmol L ⁻¹	The method by complexometry (EDTA)	NFT 90-003
Chloride (Cl ⁻)	mg L ⁻¹	Determination by silver nitrate	NF T 90-014
Sulphate (SO ₄ ²⁻)	mg L ⁻¹	Precipitation of sulfate ions in the presence of barium chloride	NFT 90-040

To determine the typology of the FSBM's effluents, a principal component analysis (PCA) was applied to the physicochemical results of a log-transformed matrix (log X+1) consisting of 92 samples and 11 parameters of wastewater physicochemical quality after a Varimax rotation. Furthermore, the Kruskal-Wallis test is used to conduct a statistical analysis of the spatial variability of the physicochemical characteristics of the effluents in the sampling points. The various calculations (e.g., Means, standard deviations, ratios, etc.) and statistical data analyses were performed using the Xlstat Software, version 2016.

RESULTS

Physicochemical Quality of Wastewater

Monitoring the physicochemical quality of the FSBM's effluents shows that the pH averages vary between 7.18 (P5) and 8.18 (P4). The WW's temperature averages are relatively homogeneous and vary between 17.64 and 19.94 °C, respectively noted at P5 and P1, while the extreme values fluctuate in a variable interval from 16.2 (P1) to 25 °C (P2). As for the degree of mineralization, the effluent physicochemical analysis reveals that the EC averages range within an interval of 2.47 (P5) and 3.97 ms cm⁻¹ (P4). This WW's strong mineralization is enhanced by the relatively high sulfate contents, which fluctuate between averages of 51.89 and 94.85 mg L⁻¹, respectively noted at P3 and P1, and the chloride concentrations, which vary between averages of 766.57 (P5) and 894.51 mg L⁻¹ (P3).

Regarding the wastewater hardness, the TH contents oscillate between averages of 508.38 (P5) and 584.52 mmol L⁻¹ (P2), while the CH averages range between 146.89 (P4) and 235.88 mmol L⁻¹ (P2) (Fig. 3).

The FSBM's effluent has a relatively high particulate load, where the TSS contents range in an interval of 6.66 and 1,277.28 mg L⁻¹, noted at P1, with averages of 192.14 and 694.15 mg L⁻¹, and turbidity ranging from 156.24 (P5) to 224.74 NTU (P3). Regarding the oxidizable and organic load, the physicochemical results show that the COD averages range between 934 and 1,151.08 mg L⁻¹ with extreme values of 56 and 2112 mg L⁻¹ noted, respectively, at P1 and P5 sampling points. As for BOD₅, the values fluctuate between 0 and 534 mg L⁻¹, with an average range of 59.6 (P5) and 115.78 mg L⁻¹ (P2) (Fig. 4).

The nutrient load of the FSBM's wastewater is characterized by total phosphorus contents varying between averages of 2 (P5) and 3.21 mg L⁻¹ (P4), with extreme values of 0.08 (P1, P3, and P5) and 7.6 mg L⁻¹ (P3). For orthophosphate, the average contents range between 0.74 (P5) and 2.23 mg L⁻¹ (P1), whereas ammonium ion concentrations vary between 0.08 and 32.8 mg/L, with an average range of 3.50 (P5) and 16.19 mg/L (P3). At the same time, the nitrite and nitrate concentrations reveal variations within an average range of 0.17–0.71 mg L⁻¹ (P1) and 0.51–1.20 mg L⁻¹ (P2), respectively (Fig. 4).

Compared to the main wastewater references in Morocco (Table 2), the effluents generated by this university campus have a physicochemical quality globally comparable to that

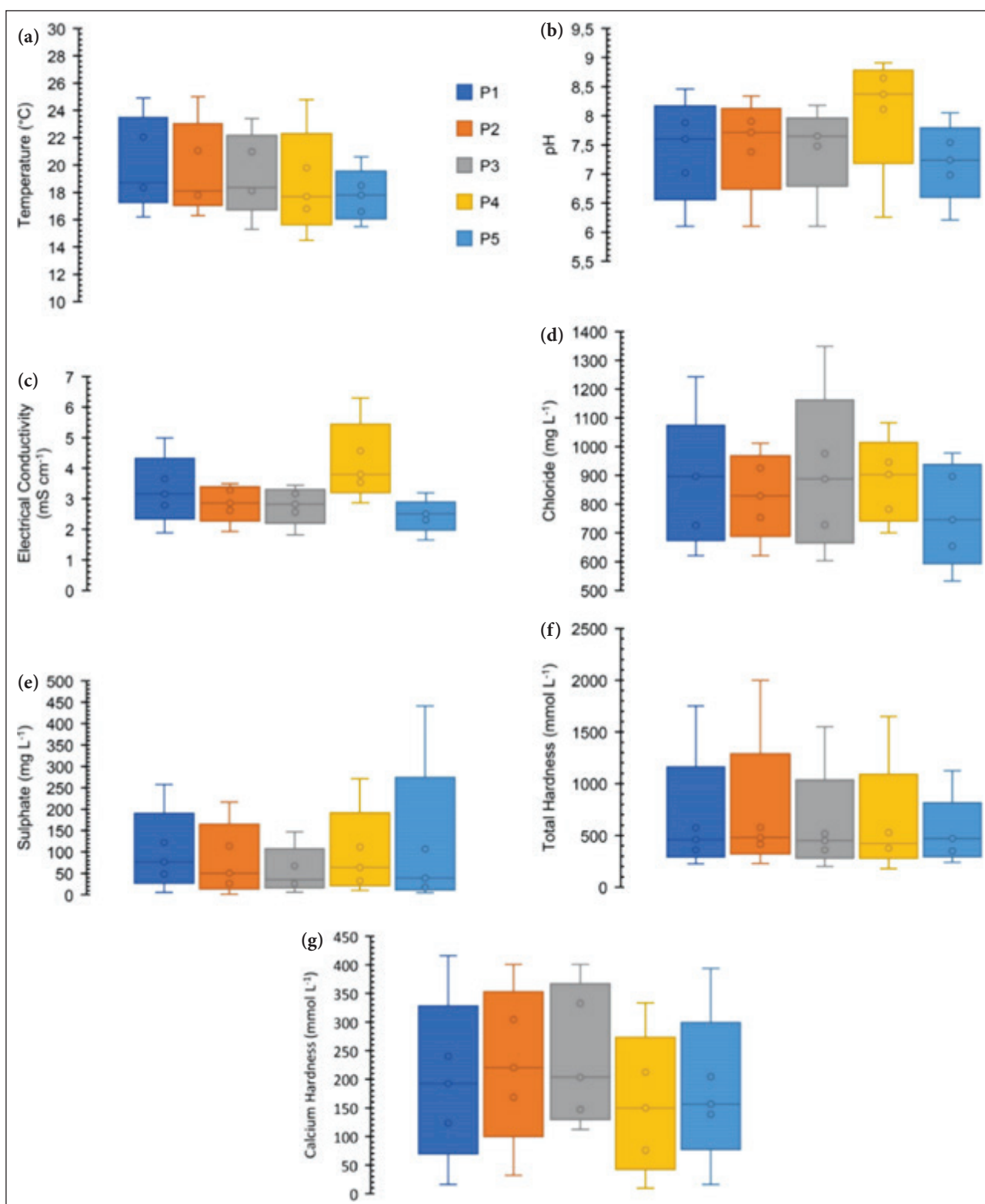


Figure 3. Variations (a) in temperature, (b) pH, (c) EC, (d) Cl⁻, (e) SO₄²⁻, (f) total hardness, and (g) calcium hardness at the sampling points. P1: Department of Chemistry and student's restaurant (n=19), P2: Department of Biology (n=19), P3: Department of Physics (n=18), P4: toilets of tutorial rooms and "West" Amphitheaters (n=21); P5: "East" Amphitheaters toilets and teachers' restaurant (n=13).

reported at the national level [22]. However, they remain non-compliant with the indirect discharge limits stipulated by Moroccan standards [23], particularly concerning pH, COD, and TSS.

Furthermore, the application of the Kruskal-Wallis test to the physicochemical data recorded at the different sampling points showed that only the parameters pH, EC, NH₄⁺, and PO₄³⁻ present a statistically significant spatial variability (Table 3).

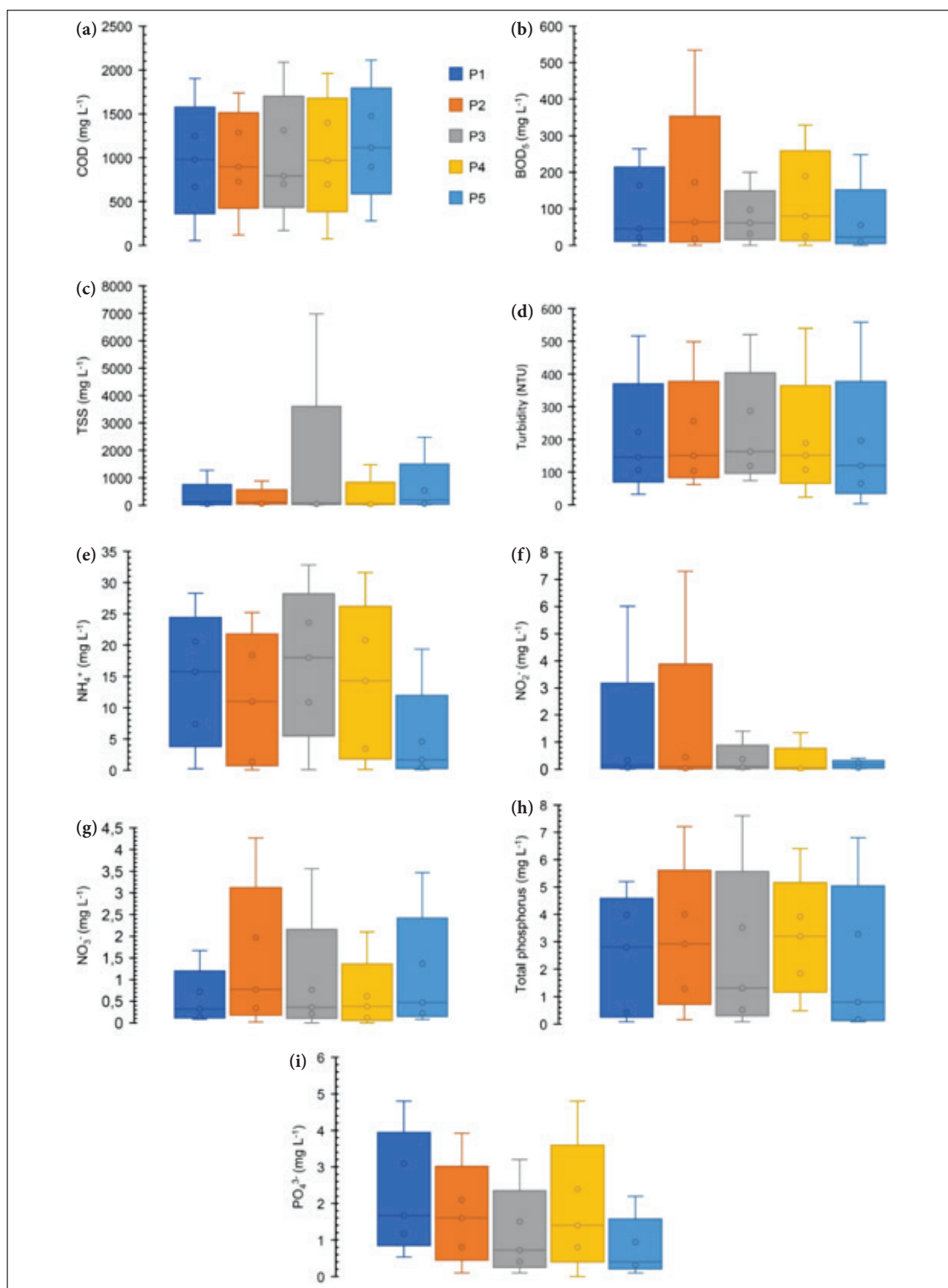


Figure 4. Variations in (a) COD, (b) BOD_5 , (c) TSS, (d) turbidity, (e) NH_4^+ , (f) NO_2^- , (g) NO_3^- , (h) total phosphorus, and (i) PO_4^{3-} at the sampling points P1: Department of Chemistry and student's restaurant ($n=19$), P2: Department of Biology ($n=19$), P3: Department of Physics ($n=18$), P4: toilets of tutorial rooms and "West" Amphitheater ($n=21$); P5: "East" amphitheater toilets and teachers' restaurant ($n=13$).

Table 2. Comparison of physicochemical parameters data obtained with reference values for wastewater in Morocco

Parameter	Unit	Range of variation	Usual range [22]	Indirect release limit values [23]
T	°C	17.64–19.55		35
pH	–	7.18–8.18		6.5–8.5
EC	mS cm ⁻¹	2.47–3.98		
Tur	NTU	156.24–224.74		
BOD ₅	mg L ⁻¹	70.5–119.05	200–400	500
COD	mg L ⁻¹	967.44–1,151.08	1,000	1,000
TSS	mg L ⁻¹	223.64–1,659.74	250–500	600
NH ₄ ⁺	mg L ⁻¹	3.50–17.55	20–80	
NO ₂ ⁻	mg L ⁻¹	0.17–3.65	<1	
NO ₃ ⁻	mg L ⁻¹	0.69–1.48	<1	
TP	mg L ⁻¹	2.002–3.99	8–16	10
PO ₄ ⁺	mg L ⁻¹	0.74–2.75		
CH	mmol L ⁻¹	171.48–239.91		
TH	mmol L ⁻¹	631.76–790.94		
Cl ⁻	mg L ⁻¹	766.57–1,232.25		
SO ₄ ²⁻	mg L ⁻¹	51.89–94.85		400

Table 3. Variability of physicochemical parameters at different sampling points (Kruskal-Wallis test, significance level=0.05)

	T	pH	EC	TSS	Tur	BOD ₅	COD	NH ₄ ⁺
p-value	0.077	<0.0001	<0.0001	0.643	0.595	0.738	0.784	0.004
	NO ₃ ⁻	NO ₂ ⁻	TP	PO ₄ ³⁻	SO ₄ ²⁻	Cl ⁻	CH	TH
p-value	0.261	0.594	0.225	0.008	0.461	0.444	0.130	0.939

Table 4. Mean values and standard deviations (Mean±SD) of different organic pollution ratios of FSBM's wastewater

	P1	P2	P3	P4	P5
COD/BOD ₅	11.57 (±12.02)	18.03 (±19.68)	16.51 (±14.8)	31.09 (±39.61)	88.74 (±99.65)
BOD ₅ /COD	0.23 (±0.24)	0.13 (±0.12)	0.08 (±0.06)	0.18 (±0.18)	0.07 (±0.08)
TSS/BOD ₅	3.67 (±4.30)	3.78 (±4.25)	6.23 (±8.01)	6.81 (±8.06)	9.64 (±8.96)
C/P	1,695.09 (±2,240.87)	899.65 (±866.77)	2,769.59 (±3,539.46)	461.30 (±302.93)	3,652.47 (±2,963.22)
C/N	472.74 (±637.09)	958.70 (±1,325.15)	575.12 (±775.83)	741.69 (±100.16)	1,939.40 (±1,968.68)
OM	338.31 (±95.44)	346.25 (±193.58)	314 (±175.36)	406.12 (±151.03)	398.08 (±119.57)

Organic Pollution of Wastewater

According to the results of the FSBM's computation of the various organic pollution ratios (Table 4), the COD/BOD₅ ratio is high and largely exceeds 3, with average values fluctuating between 11.57 (±12.02) and 88.74 (±99.65) calculated, respectively, for P1 and P5 sampling points. Conversely, the BOD₅/COD ratio averages are very low and vary between 0.07 (±0.08) and 0.23 (±0.24) noted at P5 and P1, respectively. As for the TSS/BOD₅ ratio, the average values are between 3.67 (±4.30) calculated for P1 and 9.64 (±8.96) noted in P5. The C/P ratio remains relatively high, especially at P1, P3, and P5 sampling points, and varies between averages of 461.30 (±302.93) and 3,652.47 (±2,963.22), reported at P4 and P5, respectively. Regarding the C/N ra-

tio, the average values vary between 472.74 (±637.09) and 1,939.4 (±1968.68) noted respectively at P1 and P5. The average oxidizable matter (OM) load of the wastewater ranges between 314.83 (±175.36) and 406.12 mg L⁻¹ (±151.03).

Wastewater Typology

The multivariate analysis of the FSBM's wastewater physicochemical data by PCA, with Varimax rotation, shows that the first two axes (D1 and D2) explain 36.92% of the data's ordination (Fig. 5). On the same D1*D2 factorial plane, the sampling points are distributed into three groups: The first group consists of sampling points P2, P3, and P4, which are distinguished by relatively warm (i.e., T), highly mineralized (i.e., EC), and highly oxidizable (i.e., TSS, COD, BOD₅)

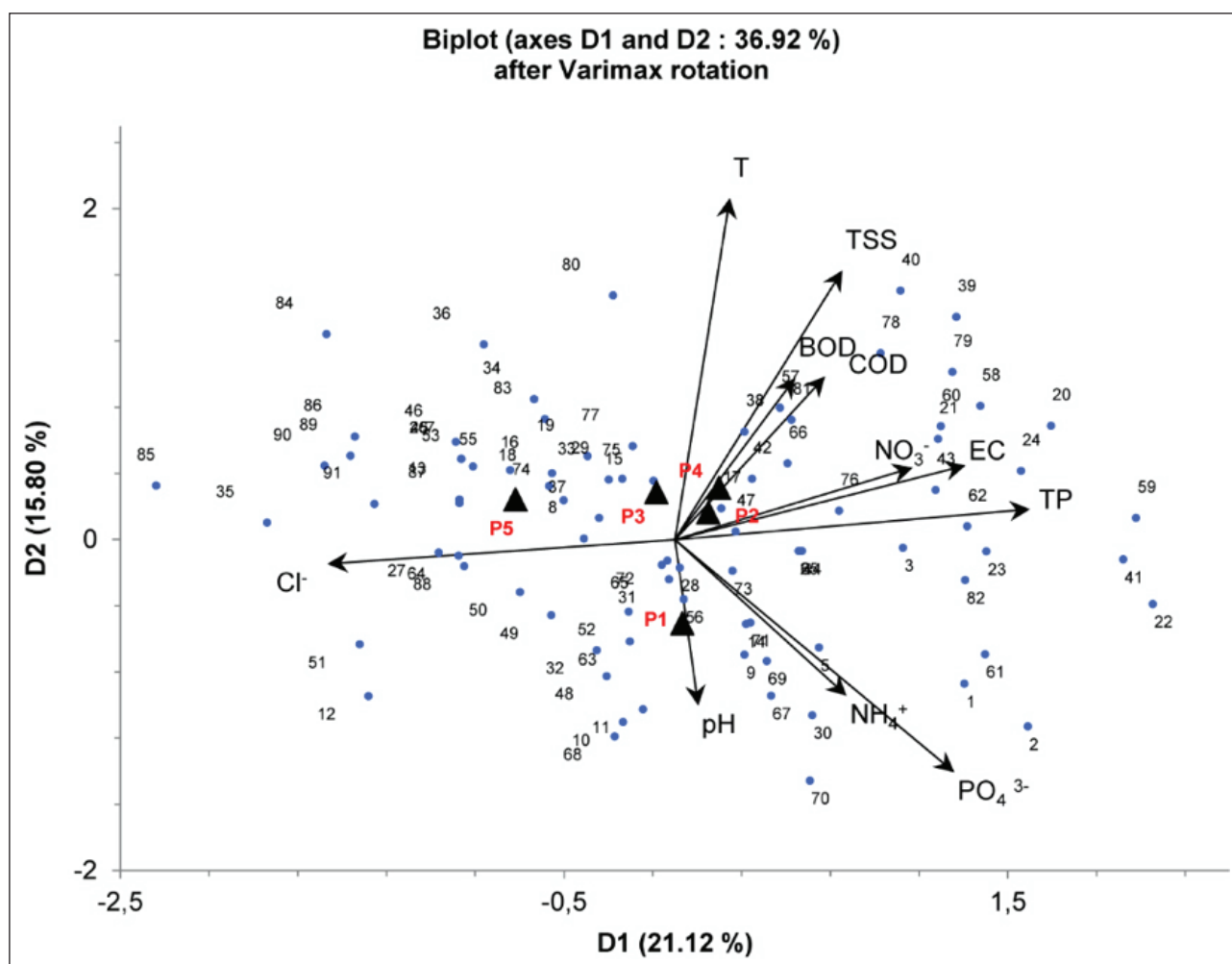


Figure 5. Representation of the ACP analysis after Varimax rotation based on physicochemical data from FSBM campus's wastewater (the dots and numbers represent to the 92 samples carried out at points P1, P2, P3, P4, and P5).

water. The second group is essentially formed by the wastewater samples from the point P5 characterized by high chloride content (i.e., Cl^-) and relatively low particulate (i.e., TSS), oxidizable (i.e., COD), and nutrient loads (i.e., TP, NH_4^+ , NO_3^-). The third group is formed by the wastewater samples from the point P1, which are slightly alkaline and characterized by a relatively high load of nitrogen and phosphorus elements (i.e., NH_4^+ , PO_4^{3-}).

DISCUSSION

Monitoring the physicochemical quality of the FSBM's effluents shows that their characteristics change globally according to their origin, which is linked to the activities in the various establishment's premises. Thus, several physicochemical parameters show a relatively significant variability (Table 4) at the same sampling point and during any study period. This variability may be associated with the release of high-complexity effluents due to the different use of water according to the practical teaching and research activities carried out within the campus's laboratories. However, rainwater contributes to the dilution of the wastewater collected by the unitary sanitation system and would thus explain the

pollutant's load decrease during rainy periods [24]. Thus, the pH of the FSBM's effluent remains relatively neutral to alkaline for all sampling points. This alkaline trend of the WW would be related to their organic nitrogenous contents (i.e., NH_4^+ : 3.50–16.19) with generally alkaline characteristics (i.e., P4) [24, 25] and to their low content of nitrite (0.17–0.71) and nitrate (0.56–1.20). This effluent's alkalinity would also be caused by the discharge of chemical solutions, especially alkaline ones, used in the different research and practical teaching activities in the laboratories (i.e., P1, P2, and P3). The effect of these chemical solutions on the laboratory effluents' pH was underlined by Novita et al. [26] (Table 5), who showed that the wastewater's high acidity of the Faculty of Agricultural Technology in Indonesia (i.e. $\text{pH}=4.28$) is related to the use of acidic solutions (i.e., H_2SO_4). These large fluctuations in effluent's acidity or alkalinity can impact the sewage system, equipment, and treatment processes, especially the biological treatment of WW [27]. Nonetheless, the pH values recorded for FSBM's effluent are still suitable for most WW treatment processes. The relatively high temperatures and mineralization (i.e., EC, SO_4^{2-} , and Cl^-) of the FSBM's effluents (i.e., P1, P2, and P3) would be associated with the liquid effluents' nature pro-

Table 5. Comparison of physicochemical characteristics of wastewater from some university campuses

University campus and reference of the study	Origin of wastewater	T (°C)	pH	EC (mS/cm)	TSS (mg/L)	BOD ₅ (mg/L)	COD (mg/L)	NH ₄ ⁺ (mg/L)	TP (mg/L)	NO ₃ ⁻ (mg/L)	NO ₂ ⁻ (mg/L)	PO ₄ ⁺ (mg/L)
Las Palmas de Gran Canaria (Spain) [28]	Wastewater from the entire campus				158	314	416	139				
Al-Hussein bin Talal (Jordan) [13]	Wastewater from the entire campus				201.3–264.8	230.7–328.5	315.1–365.6					
Al Bayt (Jordan) [36]	Wastewater from the entire campus		6.87						18.80	7.7		
XYZ (Indonesia) [26]	Wastewater from the laboratories of the Faculty of Agricultural Technology and the Faculty of Pharmacy	26–27	4.28–7.02		542.5–13.6	84.18–58.28	251.6–148.2					
Greece [40]	Typical domestic wastewater (dormitories, student dining, laundry rooms, offices, etc.)	19.1	7.5	1.267		241.6	350.2		9.8			
Higher Polytechnic School of the Coast (ESPOL) (Ecuador) [58]	Typical domestic wastewater				236	350	594					
Pereira (Colombia) [42]	Wastewater from the entire campus					177.5–460.5	395.5–971.0		13.3–11.8	0.5–4.5		11.3–9.5
Occidente (Colombia) [29]	Wastewater from the entire campus	22.20–27.80	8.04–9.20		14–202	200–609	372–1512	45.00–108.50	12.70–113.00	15–46		0.80–3.80
Guilin (China) [12]	Wastewater from student dormitories and public-use water	11–28	6.34–7.56			113.6–241.1	167.5–521.0		3.6–11.3			
Santa Cruz do (Brazil) [59]	Campus wastewater, except for teaching labs and restaurants.	19.27	6.75	1192.96		142.56	377.3		0.90			
Ouro Preto University (Brazil) [11]	Wastewater from the entire campus		7.35–8.23	0.53–0.758		171–300	403–670		4.8–6.7			
Faculty of Sciences Ain Chock (Morocco) [38]	Wastewater from university toilets				415	285	541	45.45		0.01	0.73	3
Faculty of Sciences Ben M'Sick (Morocco) (the present study)	Wastewater from the entire campus	17.64–19.55	7.18–8.18	2.47–3.98	223.64–1,659.74	70.5–119.05	967.44–1,151.08	3.50–17.55	2.002–3.99	0.69–1.48	0.17–3.65	0.74–2.75

duced by the research and practical teaching laboratories, which are generally formed of warm water (i.e., Distillation apparatus cooling) and loaded with ionic salts. This high salt load is associated with using reagents and chemicals in laboratories, which are sometimes hazardous or toxic.

At point P4, the high ammonium load can be due to the urea content of wastewater from student toilets. Moreover, this ammoniacal nitrogen load is less important at point P5, which has relatively low pH values compared to those noted at point P4. Thus, it shows a significant relationship between wastewater pH and ammoniacal nitrogen load. In addition, this wastewater's alkalinity could influence the nitrogen removal process during treatment. The pH of the FSBM's effluents varies globally between 6.1 and 8.91, indicating that nitrogen removal during treatment is primarily accomplished through bacterial transformations (i.e., nitrification and denitrification) [28]. Indeed, some bacterial nitrogen transformations in the WW treatment systems depend on energy derived from organic carbon degradation. However, others release energy used by microorganisms for their growth and survival. Therefore, nitrogen removal in these treatment systems is directly influenced by the C/N ratio; the greater the ratio, the higher the nitrogen removal. Chiu et al. [20] showed that a low C/N ratio of the effluent leads to a rapid carbon deficit and simultaneous nitrification-denitrification process at a sequential biological treatment system, which disrupts the complete removal of NH_4^+ and COD. In this regard, the high average C/N ratio values (i.e., 472.74–1939.40) recorded at the FSBM's effluents suggest that biological treatment would be suitable for removing this nitrogenous element.

The load of calcium and magnesium in the FSBM's effluents, although relatively high, is similar to the results reported by Sarria et al. [29] for the Universidad Autonoma de Occidente (Colombia) campus's wastewater (Table 5). This high hardness of the FSBM's wastewater would favor biofilm development in the sewerage network and treatment systems [30, 31]. Indeed, in biological treatment systems, divalent cations (e.g., Ca^{2+} and Mg^{2+}) can enhance the cross-linking effect of soluble extracellular polymers (EPSs) matrix [32, 33] and even improve them. Thus, this hardness would be one of the factors influencing the formation, stability, and settling of purifying biomass during biological treatment of FSBM's effluents [34, 35].

The load of the phosphorus compounds (TP and PO_4^{3-}) in the FSBM's effluents, whose characterization is essential for the good progress of the WW treatment process (i.e., their role in the biomass growth), remains relatively lower than that noted in several studies on the effluents of university campuses including the work of Ziadat et al. [36] for the WW of the university campus Al Bayt in Jordan, and Beyene and Redaie [37] for the WW of the university of Hawassa's reference hospital (Ethiopia) (Table 5). However, Chakri et al. [38] revealed a comparable phosphorus element load (i.e., 3 mg L^{-1}) to this study's findings (Table 5) on effluent from the toilets of the Faculty of Science Ain Chock-Casablanca (Morocco). Phosphorus removal from WW is strongly related to the organic load, and the C/P ratio plays a central role in treating this nutrient, which is highly removed when this

ratio is low. In the FSBM's effluents, the high values of the C/P ratio (i.e., 461.30–3652.47) indicate that a specific treatment is necessary for phosphorus removal. Indeed, several studies have shown that a high C/P ratio (e.g., $\text{C/P} > 50 \text{ mg}$) in the liquid effluent does not allow good development of the organisms accumulating phosphorus, responsible for its elimination, during treatment [39].

The particulate load of FSBM's effluent is generally high despite the low flow rate at the sampling points. These high TSS contents, comparable to those of Moroccan urban WW [22], are associated with the nature of the activities that generate these liquid effluents. Indeed, this TSS load is very high at points P1 and P5, which receive the WW from the students' (P1) and teachers' restaurant (P5), particularly loaded with organic particles, in addition to the research and practical work laboratories wastewater. Moreover, the leaching of organic and mineral solid particles during the rainy period (the maximum extreme values are recorded during the rainy period of November 2021 and January 2022) contributes to this TSS's enrichment. In addition, the high TSS levels are a risk factor for clogging and limited wastewater disinfection in several treatment systems [40]. Thus, treating the high TSS load of FSBM's Wastewater requires a combination of physical (e.g., decantation and filtration) [41] and biological processes to be implemented in the planned treatment system. A priori, providing a stilling tank for these effluents before any treatment is necessary for the early reduction of their particulate load and, at the same time, improve the efficiency of their treatment.

The high oxidizable matter (COD) and organic matter (BOD_5) loads recorded at the sampling points P1, P3, P4, and P5 for the first parameter and at P2 and P4 for the second would be associated with the FSBM's effluents richness in chemicals carried notably by laboratory effluents and organic matter from typical domestic activities (e.g., toilets, restaurants) [11]. These COD and BOD_5 values are comparable to those reported in similar studies [29–42] (Table 5). The high recorded values of oxidizable matters (OM) and COD/ BOD_5 ratio indicate that the FSBM's effluents contain a significant fraction of poorly biodegradable matters that would be related to the chemical solutions and reagents discharged by the different FSBM's laboratories. In addition, the low BOD_5/COD ratio (i.e., $\text{BOD}_5/\text{COD} < 0.5$) confirms this low biodegradability of FSBM's effluents and the presence of probably toxic chemicals that may slow down or delay the biological process of their treatment [43]. The high TSS/ BOD_5 ratio values, compared with those of Moroccan urban WW (i.e., 1.2–1.5) [18], could be explained by the low sedimentation of solid matter in the FSBM's wastewater. These TSS/ BOD_5 ratio values indicate that the effluent's particulate load is formed essentially by organic matter flakes that are difficult to settle, unlike sand, silt, and other solid matter particles.

Based on this study's findings, considering the regulatory compliance context related to the respect of discharge standards, and considering the impacts of water stress that Morocco has been undergoing in recent years, it is judicious to equip the FSBM's campus with a compact wastewater

treatment system, with low economic cost and effective to produce reusable purified water. For this purpose, biological treatment processes, often used for the purification of a wide range of WW, may constitute an option because of their adaptation to the treatment of several types of effluents and their economic advantages in comparison to other treatment processes (e.g., thermal processes, chemical oxidation) [44]. Moreover, membrane bioreactors (MBR) are highly efficient in treating complex industrial effluents [45–48]. In addition to their compact size, shape and low energy consumption, MBR systems produce good quality treated water [49–51] that can be reused, especially in watering green spaces [52–57]. However, in the case of FSBM's effluents, variability in organic, nitrogen, and phosphorus load could negatively impact the performance of any proposed biological treatment system, especially during the rainy season and possibly during the summer vacation due to a lack of substrate for biomass feeding. Thus, homogenization and feed flow regulation are essential before the biological treatment phase.

CONCLUSION

The physicochemical characterization of the FSBM's effluents carried out to apply the "zero discharge" approach via their internal treatment and reuse revealed that they are globally alkaline, with homogeneous average temperatures and strong mineralization linked to high concentrations of sulfate, chloride, Ca^{2+} and Mg^{2+} . These WW also contain high levels of TSS and oxidizable (COD) and organic matters (BOD_5) exceeding the limit values recommended by Moroccan standards of indirect discharge, unlike nutrients (i.e., total phosphorus, orthophosphate, ammonium ion, nitrite, and nitrate).

The multivariate analysis performed by PCA on the effluents' physicochemical data revealed that their heterogeneous nature is linked to their origin. The effluents from the Biology (P2) and Physics (P3) departments, the tutorial room's toilets, and the "West" Amphitheatre (P4) are relatively warm, alkaline, highly mineralized and loaded with oxidizable matters. The WW coming from the "East" Amphitheatre's toilets and the teachers' restaurant (P5) is characterized by high chloride contents, relatively low particulate and oxidizable loads, and nutrients. At the same time, the wastewater generated by the department of Chemistry and by the student's restaurant (P1) is slightly alkaline and has a relatively high nitrogen and phosphorus load.

The pollution ratios (COD/BOD_5 , BOD_5/COD , TSS/BOD_5 , COD/TP , and COD/NH_4^+) show that the FSBM's effluent would be loaded with poorly biodegradable substances with a heterogeneous character. This character would be linked to chemical products from the research laboratories' effluents and the departments' practical work. Despite this profile and their organic loads, the FSBM's effluents could be treated using a biological purification system. However, this must be preceded by a physicochemical treatment to eliminate non-biodegradable chemical substances. Such a choice of WW treatment system requires prior experimental investigations and laboratory tests.

DATA AVAILABILITY STATEMENT

The author confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

FUNDING STATEMENT

The research leading to these results was independently financed by Hassan II University of Casablanca as part of the "Smart Campus 2020" project.

REFERENCES

- [1] J. M. García-Ruiz, J. I. López-Moreno, S. M. Vicente-Serrano, T. Lasanta-Martínez, and S. Beguería, "Mediterranean water resources in a global change scenario," *Earth-Science Reviews*, Vol. 105(3–4), pp. 121–139, 2011. [\[CrossRef\]](#)
- [2] S. B. Gray, and S. M. Brady, "Plant developmental responses to climate change," *Developmental Biology*, Vol. 419(1), pp. 64–77, 2016. [\[CrossRef\]](#)
- [3] A. D. Teshager, P. W. Gassman, J. T. Schoof, and S. Secchi, "Assessment of impacts of agricultural and climate change scenarios on watershed water quantity and quality, and crop production," *Hydrology and Earth System Sciences*, Vol. 20(8), pp. 3325–3342, 2016. [\[CrossRef\]](#)
- [4] J. F. Schyns, and A. Y. Hoekstra, "The added value of water footprint assessment for national water policy: a case study for Morocco," *PLoS One*, Vol. 9(6), pp. 1–14, 2014. [\[CrossRef\]](#)
- [5] Conseil Economique, Social et Environnemental (CESE), "La gouvernance par la gestion intégrée des ressources en eau au Maroc: Levier fondamental de développement durable," *Auto-Saisine n° 15*, Maroc: Chem Pap., 2014. <https://www.cese.ma/media/2020/10/Rapport-Gouvernance-des-ressources-en-eau.pdf> Accessed on Mar 23, 2023.
- [6] F. Taheripour, W. E. Tyner, I. Haqiqi, E. Sajedinia, "Water Scarcity in Morocco: Analysis of Key Water Challenges," Maroc: Water Global Practice, 2020. <https://openknowledge.worldbank.org/server/api/core/bitstreams/4338ca29-bf9e-5b4a-bea8-4e7a8867aee2/content> Accessed on Mar 23, 2023.
- [7] Royaume du Maroc, "Ministère de la transition énergétique et du Développement Durable," 2015. <https://www.environnement.gov.ma/fr/air/9-non-categorise/92-strategie-de-l-eau> Accessed on Mar 16, 2023.

- [8] Royaume du Maroc, Ministère de l'énergie des Mines et du Développement Durable (MEMDD) et le Secrétariat d'Etat chargé du Développement Durable (SECD), "Strategie nationale de développement durable 2030," Rapport final, Maroc: MEMDD, 2017. https://www.environnement.gov.ma/images/a_la_une/JANVIER2022/Rapport_Strategie_Nationale_DD_juin2017_Mai_2017_Web.pdf Accessed on Mar 16, 2023.
- [9] Royaume du Maroc, "Dahir n° 1-19-113 du 7 hijra 1440 (9 août 2019) portant promulgation de la loi-cadre n° 51-17 relative au système d'éducation, de formation et de recherche scientifique," Bulletin Officiel, Vol. 6944, pp. 1967–1980, 2019.
- [10] L. C. Alves, "Caracterização e tratamento de efluentes de laboratório de análises químicas," Master's thesis, Brazil: Federal University of Uberlândia, 2002.
- [11] S. M. Bertolino, C. F. Carvalho, and S. F. Aquino, "Caracterização e biodegradabilidade aeróbia e anaeróbia dos esgotos produzidos em campus universitário," Engenharia Sanitária e Ambiental, Vol. 13, pp. 271–277, 2008. [CrossRef]
- [12] W. Zhang, D. Wang, and Y. Jin, "Use of a ceramic membrane bioreactor (CMBR) to treat wastewater at Guilin University of Technology," Water Practice and Technology, Vol. 12(2), pp. 453–462, 2017. [CrossRef]
- [13] A. Dahamsheh, and M. Wedyan, "Evaluation and assessment of the performance of Al-Hussein bin Talal University (AHU) wastewater treatment plants," International Journal of Advanced and Applied Sciences, Vol. 4(1), pp. 84–89, 2017. [CrossRef]
- [14] Hassan II University of Casablanca, "Site of Hassan II University of Casablanca," 2022. <https://www.univh2c.ma/#> Accessed on Dec 20 2022.
- [15] J. Rodier, B. Legube, and N. Merlet, "L'analyse de l'eau," (9th ed.), Dunod, 2009.
- [16] D. Belghyti, Y. El guamri, G. Ztit, L. Ouahidi, B. Joti, A. Harchrass, and H. Bounouira, "Caractérisation physico-chimique des eaux usées d'abattoir en vue de la mise en œuvre d'un traitement adéquat: cas de Kénitra au Maroc," Afrique Science, Vol. 5(2), pp. 199–216, 2009. [CrossRef]
- [17] Office National d'Eau Potable (ONEP), "Gamme habituel des eaux usées urbaines au Maroc - ONEP," Approche de la typologie des eaux usées urbaines au Maroc, Maroc: ONEP et GTZ, Rabat, 1998.
- [18] I. Kanbouchi, S. Souabi, A. Chtaini, and M. A. Aboulhassan, "Évaluation de la pollution des eaux usées mixtes collectées par le réseau d'assainissement de la ville de Mohammedia: Cas d'un collecteur principal," Les technologies de laboratoire, Vol. 8(34), pp. 162–171, 2014.
- [19] A. A. Al Ali, V. Naddeo, S. W. Hasan, and A. F. Yousef, "Correlation between bacterial community structure and performance efficiency of a full-scale wastewater treatment plant," Journal of Water Process Engineering, Vol. 37, pp. 1–10, 2020. [CrossRef]
- [20] Y. C. Chiu, L. L. Lee, C. N. Chang, and A. C. Chao, "Control of carbon and ammonium ratio for simultaneous nitrification and denitrification in a sequencing batch bioreactor," International Biodegradation & Biodegradation, Vol. 59(1), pp. 1–7, 2007. [CrossRef]
- [21] Y. Jia, S. Lv, T. Yang, L. Zhang, and G. Jiang, "Effect of COD/NH₄⁺-N and influent pH on the simultaneous nitrification and denitrification by using a sequencing batch reactor," International Conference on Digital Manufacturing & Automation, pp. 604–607, 2010. [CrossRef]
- [22] Office National d'Eau Potable (ONEP), "Gamme habituel des eaux usées urbaines au Maroc," Maroc: ONEP, 2005.
- [23] Royaume du Maroc, "Décret n°2-04-553 du 13 hijra 1425/24 janvier 2005 relatif aux déversements, écoulements, rejets, dépôts directs ou indirects dans les eaux superficielles ou souterraines: Valeurs limites de rejets indirects," Bulletin Officiel, Vol. 5292, pp. 162–164, 2005.
- [24] L. L. Alborno, T. C. Centurião, A. Giacobbo, J. Zoppas-Ferreira, and A. M. Bernardes, "Influence of rain events on the efficiency of a compact wastewater treatment plant: a case study on a university campus aiming water reuse for agriculture," Environmental Science and Pollution Research, Vol. 27, pp. 41350–41360, 2020. [CrossRef]
- [25] P. Svehla, J. Radechovsky, H. Hrnčirova, L. Páček, and J. Bartáček, "Effect of influent nitrogen concentration on the feasibility of short-cut nitrification during wastewater treatment in activated sludge systems," Chemical Papers, Vol. 69(7), pp. 921–929, 2015. [CrossRef]
- [26] E. Novita, I. Andriyani, E. S. Hartiningsih, and H. A. Pradana, "Characterisation of Laboratory Wastewater for Planning Wastewater Treatment Plants in a University Campus in Indonesia," Ecology, Environment and Conservation, Vol. 28, pp. 45–50, 2022. [CrossRef]
- [27] Amouei, H. Asgharnia, H. Fallah, H. Faraji, R. Barari, and D. Naghipour, "Characteristics of effluent wastewater in hospitals of Babol University of Medical Sciences, Babol, Iran," Health Scope, Vol. 4(2), pp. 1–4, 2015. [CrossRef]
- [28] J. H. Melián, J. Araña, O. G. Díaz, M. A. Bujalance, and J. D. Rodríguez, "Effect of stone filters in a pond-wetland system treating raw wastewater from a university campus," Desalination, Vol. 237, pp. 277–284, 2009. [CrossRef]
- [29] N. V. Sarria, D. M. R. Velasco, D. A. L. Chávez, H. D. M. Ríos, M. A. G. Ayerbe, and C. E. G. López, "Struvite and hydroxyapatite recovery from wastewater treatment plant at Autónoma de Occidente University, Colombia," Case Studies in Chemical and Environmental Engineering, Vol. 6, pp. 1–12, 2022. [CrossRef]

- [30] Y. Ye, N. Ling, R. Jiao, Q. Wu, Y. Han, and J. Gao, "Effects of Ca^{2+} and Mg^{2+} on the biofilm formation of *Cronobacter sakazakii* strains from powdered infant formula," *Journal of Food Safety*, Vol. 35(3), pp. 416–421, 2015. [\[CrossRef\]](#)
- [31] T. Wang, S. Flint, and J. Palmer, "Magnesium and calcium ions: roles in bacterial cell attachment and biofilm structure maturation," *Biofouling*, Vol. 35(9), pp. 959–974, 2019. [\[CrossRef\]](#)
- [32] L. Liu, D. W. Gao, M. Zhang, and Y. Fu, "Comparison of Ca^{2+} and Mg^{2+} enhancing aerobic granulation in SBR," *Journal of Hazardous Materials*, Vol. 181(1-3), pp. 382–387, 2010. [\[CrossRef\]](#)
- [33] T. Kobayashi, Y. Hu, and K. Q. Xu, "Impact of cationic substances on biofilm formation from sieved fine particles of anaerobic granular sludge at high salinity," *Bioresource Technology*, Vol. 257, pp. 69–75, 2018. [\[CrossRef\]](#)
- [34] M. Cui, Y. Li, Y. Sun, H. Wang, M. Li, L. Li, and W. Xu, "Study on adsorption performance of $\text{MgO}/\text{Calcium}$ alginate composite for congo red in wastewater," *Journal of Polymers and the Environment*, Vol. 29(12), pp. 3977–3987, 2021. [\[CrossRef\]](#)
- [35] Y. Kim, J. Yu, S. Jeong, J. Kim, S. Park, H. Bae, ..., and T. Lee, "Differences in the effects of calcium and magnesium ions on the anammox granular properties to alleviate salinity stress," *Applied Sciences*, Vol. 12(1), pp. 19, 2021. [\[CrossRef\]](#)
- [36] H. Ziadat, M. Jiries, and I. Alojail, "Accumulation of Heavy Metals on Soil Irrigated with Treated Wastewater at Al al-Bayt University-Jordan," *Advances in Science and Engineering Technology International Conferences*, Dubai, United Arab Emirates, 26 March - 10 April 2019, Institute of Electrical and Electronics Engineers, pp. 1–6, 2019. [\[CrossRef\]](#)
- [37] H. Beyene, and G. Redaie, "Assessment of waste stabilization ponds for the treatment of hospital wastewater: the case of Hawassa University Referral Hospital," *World Applied Sciences Journal*, Vol. 15(1), pp. 142–150, 2011.
- [38] N. Chakri, B. E. Amrani, F. Berrada, and F. Amraoui, "Study of wastewater treatment's scenarios of the faculty of sciences-ain chock, Casablanca," *Advanced Intelligent Systems Applied to Environment*, pp. 176–187, 2019. [\[CrossRef\]](#)
- [39] T. M. C. M. Mino, M. C. M. Van Loosdrecht, and J. J. Heijnen, "Microbiology and biochemistry of the enhanced biological phosphate removal process," *Water Research*, Vol. 32(11), pp. 3193–3207, 1998. [\[CrossRef\]](#)
- [40] V. Papaevangelou, G. D. Gikas, and V. A. Tsihrantzis, "Effect of operational and design parameters on the performance of pilot-scale vertical flow constructed wetlands treating university campus wastewater," *Water Resources Management*, Vol. 30(15), pp. 5875–5899, 2016. [\[CrossRef\]](#)
- [41] S. I. Abou-Elela, G. Golinielli, E. M. Abou-Taleb, and M. S. Hellal, "Municipal wastewater treatment in horizontal and vertical flows constructed wetlands," *Ecological Engineering*, Vol. 61, pp. 460–468, 2013. [\[CrossRef\]](#)
- [42] J. L. Osorio Tejada, M. Varon-Hoyos, and T. Morales-Pinzon, "Comprehensive water footprint of a University Campus in Colombia: Impact of wastewater treatment modeling," *Water Air Soil Pollution*, Vol. 233, pp. 174, 2022. [\[CrossRef\]](#)
- [43] P. Kajitvichyanukul, and N. Suntronvipart, "Evaluation of biodegradability and oxidation degree of hospital wastewater using photo-Fenton process as the pretreatment method," *Journal of Hazardous Materials*, Vol. 138(2), pp. 384–391, 2006. [\[CrossRef\]](#)
- [44] R. Sathya, M. V. Arasu, N. A. Al-Dhabi, P. Vijayaraghavan, S. Ilavenil, and T. S. Rejiniemon, "Towards sustainable wastewater treatment by biological methods—A challenges and advantages of recent technologies," *Urban Climate*, Vol. 47, pp. 1–18, 2023. [\[CrossRef\]](#)
- [45] T. Stephenson, S. Judd, B. Jefferson, and K. Brindle, "Membrane bioreactors for wastewater treatment," IWA Publishing, 2000.
- [46] P. Artiga, E. Ficara, F. Malpei, J. M. Garrido, R. Mendez, "Treatment of two industrial wastewaters in a submerged membrane bioreactor," *Desalination*, Vol. 179(1-3), pp. 161–169, 2005. [\[CrossRef\]](#)
- [47] F. Alberti, B. Bienati, A. Bottino, G. Capannelli, A. Comite, F. Ferrari, and R. Firpo, "Hydrocarbon removal from industrial wastewater by hollow-fiber membrane bioreactors," *Desalination*, Vol. 204(1-3), pp. 24–32, 2007. [\[CrossRef\]](#)
- [48] S. Hebabaze, "Contribution à la mise en place d'une approche décentralisée de gestion intégrée de l'eau à Casablanca : Étude de la performance de système d'épuration d'appoint des effluents agroalimentaires à Naturex et caractérisation-traitement expérimental des eaux pluviales à la Faculté des Sciences Ben M'Sik," PhD thesis, Morocco: Hassan II University of Casablanca, 2016.
- [49] Gresle, V. Lazarova, and H. Suty, "Intérêts techniques et économiques du traitement membranaire en vue du recyclage," *Techniques Sciences Methodes-Genie Urbain Genie Rural*, Vol. 12, pp. 111–136, 2007. [\[CrossRef\]](#)
- [50] F. G. Kootenaei, and H. Aminirad, "Membrane biological reactors (MBR) and their applications for water reuse," *International Journal of Advanced Biological and Biomedical Research*, Vol. 2(7), pp. 2208–2216, 2014.
- [51] B. Sawadogo, "Traitement des eaux usées industrielles par des procédés membranaires sous climat sahélien: cas des eaux usées de brasserie au Burkina Faso," PhD thesis, France: University of Montpellier, 2018.
- [52] J. Hoinkis, S. A. Deowan, V. Panten, A. Figoli, R. R. Huang, and E. Drioli, "Membrane bioreactor (MBR) technology— a promising approach for industrial water reuse," *Procedia Engineering*, Vol. 33, pp. 234–241, 2012. [\[CrossRef\]](#)

- [53] K. Chon, S. H. Kim, and J. Cho, "Removal of N-nitrosamines in a membrane bioreactor and nano-filtration hybrid system for municipal wastewater reclamation: process efficiency and mechanisms," *Bioresource Technology*, Vol. 190, pp. 499–507, 2015. [\[CrossRef\]](#)
- [54] T. Melin, B. Jefferson, D. Bixio, C. Thoeye, W. De Wilde, J. De Koning, and T. Wintgens, "Membrane bioreactor technology for wastewater treatment and reuse," *Desalination*, Vol. 187, pp. 271–282, 2006. [\[CrossRef\]](#)
- [55] S. J. Judd, "The status of industrial and municipal effluent treatment with membrane bioreactor technology," *Chemical Engineering Journal*, pp. 1–19, 2015.
- [56] K. Bani-Melhem, Z. Al-Qodah, M. Al-Shannag, A. Qasaimeh, M. R. Qtaishat, and M. Alkasrawi, "On the performance of real grey water treatment using a submerged membrane bioreactor system," *Journal of Membrane Science*, Vol. 476, pp. 40–49, 2015. [\[CrossRef\]](#)
- [57] Kim, D. C. Choi, J. Lee, H. R. Chae, J. H. Jang, C. H. Lee, P. K. Park, and Y. J. Won, "Preparation and application of patterned hollow-fiber membranes to membrane bioreactor for wastewater treatment," *Journal of Membrane Science*, Vol. 490, pp. 190–196, 2015. [\[CrossRef\]](#)
- [58] B. Merchán-Sanmartín, P. Carrión-Mero, S. Suárez-Zamora, M. Aguilar-Aguilar, O. Cruz-Cabrera, K. Hidalgo-Calva, and F. Morante-Carballo, "Sanitary Sewerage Master Plan for the Sustainable Use of Wastewater on a University Campus," *Water*, Vol. 14(15), pp. 1–23, 2022. [\[CrossRef\]](#)
- [59] F. P. Da Silva, C. A. Lutterbeck, G. S. Colares, G. A. Oliveira, L. R. Rodrigues, N. Dell'Osbel, and Ê. L. Machado, "Treatment of university campus wastewaters by anaerobic reactor and multi-stage constructed wetlands," *Journal of Water Process Engineering*, Vol. 42, pp. 2–9, 2021. [\[CrossRef\]](#)



Research Article

Appraisal of reclaimed asphalt pavement as coarse aggregates in cement concrete

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ARTICLE INFO

Article history

Received: 27 June 2023

Revised: 24 October 2023

Accepted: 27 December 2023

Key words:

Concrete construction; Coarse aggregates; Mechanical properties; Performance evaluation; Reclaimed asphalt pavement (RAP)

ABSTRACT

This systematic literature review evaluates reclaimed asphalt pavement (RAP) in concrete construction, targeting reduced natural aggregate use and lower construction carbon footprint. It comprehensively covers RAP in concrete, including mechanical properties, durability, test methods, mix design, performance, influencing factors, RAP content, processing, admixtures, curing, and environmental aspects. RAP concrete matches traditional concrete mechanically while increasing sustainability through waste reduction. Durability parameters, like permeability, freeze-thaw resistance, and chloride penetration, suggest long-term structural enhancement. Reliable testing methods and standards are vital for RAP in concrete assessment. The review explores RAP in mix design, considering content, gradation, and processing. Admixtures and additives optimize RAP concrete. Curing and environmental conditions influence RAP concrete performance. Gaps indicate a need for long-term studies, understanding mechanisms, specific environmental exploration, standardized testing, and economic assessment. The study recommends future research directions to guide sustainable construction practices.

Cite this article as: Tiza MT, Agunwamba J, Okafor F. Appraisal of reclaimed asphalt pavement as coarse aggregates in cement concrete. Environ Res Tec 2024;7(1)27–40.

INTRODUCTION

The use of Reclaimed Asphalt Pavement (RAP) as coarse aggregates in concrete construction has gained significant attention in recent years. RAP refers to the recycled materials obtained from old asphalt pavements that are crushed and reused as aggregates in new concrete mixes [1]. This practice of utilizing RAP in concrete construction holds great promise for addressing sustainability concerns, reducing waste, and conserving natural resources.

The importance and relevance of evaluating the performance of RAP in concrete construction cannot be overstated [2]. With the increasing demand for concrete as a primary building material, there is a pressing need to explore alternative solutions that can enhance the sustainability and efficiency of construction practices. By incorporating RAP

as coarse aggregates, we can potentially reduce the reliance on traditional virgin aggregates, which require extensive mining and extraction processes. This, in turn, can help conserve natural resources and minimize the environmental impact associated with aggregate production [3].

The research objectives of this literature review are to critically examine the existing body of knowledge on the performance evaluation of RAP as coarse aggregates in concrete construction and to identify gaps in the current understanding. By reviewing previous studies, we aim to gain insights into the effects of using RAP on various concrete properties and performance indicators, such as compressive strength, durability, workability, and long-term behavior [4]. Furthermore, this literature review seeks to provide a comprehensive overview of the methodologies, experimental setups, and performance evaluation parameters used in previous research.

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Figure 1. Pictorial representation of reclaimed asphalt pavement (RAP). Source: Field.

The scope of this literature review encompasses a wide range of scholarly articles, conference papers, and industry reports that are relevant to the topic of evaluating RAP in concrete construction. The search strategy includes comprehensive searches of reputable databases and the inclusion of publications that have investigated the use of RAP as coarse aggregates, the performance of RAP-concrete mixtures, and the influence of various factors, such as RAP content, processing techniques, and mix design considerations [5]. Figure 1 provides a pictorial representation of RAP.

Theoretical Framework

The conceptual framework for the performance evaluation of RAP as coarse aggregates in concrete construction encompasses several key components that provide a theoretical foundation for understanding the topic. To begin with, it is essential to define and explain the key terms involved in this framework [6].

RAP refers to the recycled materials obtained from old asphalt pavements through the process of crushing and re-using them as aggregates in new concrete mixes. Concrete, on the other hand, is a composite material composed of cement, aggregates (including coarse aggregates), water, and other additives. Coarse aggregates are an essential component of concrete, providing strength, stability, and bulk to the mixture [7].

The theoretical foundations of this conceptual framework are rooted in concrete properties, performance evaluation, and sustainable construction practices. Concrete properties such as compressive strength, durability, workability, and long-term behavior play a crucial role in assessing its overall performance. Understanding how the incorporation of

RAP as coarse aggregates influences these properties is vital for evaluating its effectiveness in concrete construction [8].

Performance evaluation in the context of RAP as coarse aggregates involves assessing the effects of RAP on concrete properties and performance indicators. This includes examining the influence of various factors such as RAP content, processing techniques, mix design considerations, and the use of appropriate testing methodologies [9]. By analyzing previous research studies and experimental data, the framework aims to establish a comprehensive understanding of the performance of RAP-concrete mixtures [9].

Sustainable construction practices form an integral part of the conceptual framework, as the utilization of RAP as coarse aggregates aligns with the principles of sustainability. By reducing the reliance on traditional virgin aggregates, which require extensive mining and extraction processes, the use of RAP contributes to resource conservation and environmental preservation. This framework aims to explore the environmental benefits, economic viability, and social implications of incorporating RAP in concrete construction [10].

Literature Search Strategy

The literature search strategy for the performance evaluation of RAP as coarse aggregates in concrete construction involves a systematic approach to identify relevant literature. This section outlines the description of the search criteria, databases used, inclusion and exclusion criteria, and justification for the selection of sources.

To conduct a comprehensive literature search, a range of search criteria is employed. These criteria typically include keywords related to the research topic, such as "reclaimed

Table 1. A summary of performance evaluation of RAP in concrete construction

S/N	Aspect	Summary	Reference
1	Performance evaluation of RAP in concrete	Assesses the suitability and effectiveness of RAP as coarse aggregates in concrete construction. Examines influence on concrete properties, testing methods, factors affecting performance, comparisons with conventional concrete, case studies, and challenges.	[14, 15]
2	Influence on concrete properties	Evaluates RAP's impact on mechanical properties (compressive, tensile, flexural strength) and durability properties (permeability, freeze-thaw resistance, chloride ion penetration).	[16]
3	Testing methods and standards	Considers concrete mix design, standardized testing procedures, and guidelines for reliable assessment of RAP concrete.	[17]
4	Factors affecting RAP performance	Explores RAP content, gradation, processing techniques (crushing, screening, blending), use of additives, and curing conditions as influential factors.	[18]
5	Performance comparisons with conventional concrete	Assesses strength, durability, long-term performance, and structural behavior of RAP concrete in comparison to conventional concrete.	[19]
6	Case studies and experimental research	Reviews studies on RAP performance, covering parameters such as RAP content, processing methods, performance testing, and field applications.	[20]
7	Challenges and limitations	Considers potential effects on workability, mixture consistency, fresh and hardened concrete properties, and the need for quality control measures.	[21]

RAP: Reclaimed asphalt pavement.

asphalt pavement," "RAP," "concrete," "coarse aggregates," "performance evaluation," and "construction." Boolean operators like "AND" and "OR" are used to combine these keywords to refine the search results. The search also included specific terms related to concrete properties, testing methods, and sustainability.

Databases from reputable academic platforms, such as PubMed, Scopus, Web of Science, and Engineering Village, are utilized to identify relevant literature. These databases cover a wide range of disciplines, including civil engineering, materials science, construction, and sustainability. Additionally, relevant industry-specific databases and resources may be explored to include practical insights and case studies.

The justification for the selection of these sources lies in their ability to contribute to the research objectives and address the research questions [11]. Scholarly articles undergo a rigorous peer-review process, ensuring the accuracy, validity, and scientific merit of the research. Conference papers, on the other hand, provide insights into cutting-edge research and emerging trends. Industry reports and technical documents offer practical knowledge and real-world applications [12]. By incorporating a range of sources, the literature review aims to provide a comprehensive understanding of the performance evaluation of RAP as coarse aggregates in concrete construction, considering both theoretical and practical perspectives [13].

Performance Evaluation of RAP in Concrete Construction

The evaluation of RAP as coarse aggregates in concrete construction is essential to understand its suitability and effectiveness, encompassing various aspects of performance assessment [14]. This section covers its impact on concrete properties, testing methods, performance factors, compari-

sons with conventional concrete, case studies, and associated challenges [15]. RAP's influence on concrete properties, including mechanical (e.g., compressive, tensile, and flexural strength) and durability properties (e.g., permeability, freeze-thaw resistance, chloride ion penetration), is a key consideration for assessing its overall impact [16].

Testing methods and standards are crucial, ensuring a consistent and reliable assessment of RAP concrete by offering standardized procedures and guidelines for evaluation [17]. Performance factors such as RAP content, gradation, processing techniques, admixtures, curing conditions, and environmental factors must be examined to optimize RAP use in concrete mixtures [18]. Comparing RAP concrete's performance with conventional concrete involves assessing strength, durability, long-term behavior, and load-carrying capacity, confirming its suitability for various applications [19]. In this study, Table 1 provides a comprehensive summary of the Performance Evaluation of RAP in Concrete Construction.

Case studies and experimental research offer valuable insights, with a focus on parameters like RAP content, processing methods, performance testing, and field applications [20]. Despite potential benefits, challenges and limitations must be addressed, including workability, fresh and hardened concrete properties, and the need for quality control measures to ensure successful RAP utilization in concrete construction projects [21]. Figure 2 illustrates the screening process for RAP, depicting the steps in processing RAP for concrete applications.

Mechanical Properties

Evaluating the mechanical properties of RAP in concrete construction is essential to gauge its performance and suitability as an alternative to traditional aggregates [22]. The



Figure 2. Pictorial representation of screening of RAP. Source: Field work.

primary mechanical property to consider is compressive strength, measuring a concrete's load-carrying capacity [23]. This involves standardized compression tests on concrete specimens containing varying RAP percentages, following testing standards like ASTM C39, to assess RAP's impact on strength [24].

Tensile strength, another crucial property, determines concrete's ability to resist tension forces, particularly vital in structures under tensile stress. Various methods like the splitting tensile test help measure tensile strength and assess RAP's influence on structural performance [25]. Flexural strength assesses a material's resistance to bending and is important for elements like beams and slabs. Third-point or center-point loading tests on beam specimens evaluate the impact of RAP on flexural strength and cracking behavior [26].

Additional properties like modulus of elasticity and Poisson's ratio, which influence concrete's stiffness and lateral strain response, are also considered when incorporating RAP. These properties provide insights into the material's structural behavior [27]. Evaluating mechanical properties should take into account factors like RAP content percentage, aggregate grading, mix design, curing conditions, and testing procedures [28]. Systematic variation of these parameters through comprehensive testing allows researchers to understand the effects of RAP on concrete's mechanical properties and identify optimal mix proportions [29].

In conclusion, assessing mechanical properties like compressive, tensile, and flexural strength is essential to understand RAP's performance in concrete construction. This knowledge provides insights into the benefits and limitations of using RAP in concrete mixtures, promoting sustainable and resource-efficient construction practices [30]. Table 2 provides a summary of mechanical properties. This table offers a comprehensive overview of the mechanical characteristics of RAP in concrete, highlighting key aspects crucial for understanding its suitability and effectiveness as a replacement for conventional aggregates.

Durability Properties

Evaluation of durability properties plays a vital role in assessing the performance of RAP as coarse aggregates in concrete construction [31]. Permeability, a crucial property, assesses the concrete's resistance to water and liquid penetration. Methods like the water permeability test and rapid chloride ion penetration test (RCPT) gauge RAP concrete's moisture resistance and its potential to counter moisture-related deterioration [32]. Freeze-thaw resistance, another critical property, focuses on the concrete's ability to withstand the damaging effects of freezing and thawing cycles in cold climates. Evaluating freeze-thaw resistance involves subjecting specimens to multiple freeze-thaw cycles to assess changes in mass, volume, strength, and visual appearance [33]. Additionally, chloride ion penetration

Table 2. A summary of mechanical properties

S/N	Mechanical properties of RAP concrete	Summary	Reference
1	Compressive strength	Compressive StrengthMeasures concrete's resistance to compressive forces. Standardized compression tests assess RAP concrete strength. Comparisons made to conventional concrete strength.	[22–24]
2	Tensile strength	Tensile StrengthEvaluates concrete's ability to resist tension forces. Splitting tensile or direct tension tests measure RAP concrete tensile strength. Enhances structural performance.	[22, 25]
3	Flexural strength	Flexural StrengthAssesses concrete's resistance to bending or flexure. Third-point or center-point loading tests determine RAP concrete flexural strength and cracking behavior.	[22, 26]
4	Modulus of elasticity and poisson's ratio	Modulus of Elasticity and Poisson's RatioMeasures concrete's stiffness and lateral strain response. Influence structural behavior. Variation with RAP inclusion provides insights into RAP concrete behavior.	[22, 27]
5	Factors influencing results	Factors Influencing ResultsConsiderations for evaluating mechanical properties: RAP content, grading, mix design, curing conditions, and testing procedures. Optimal mix proportions determined for performance.	[28, 29]

RAP: Reclaimed asphalt pavement.

Table 3. Durability properties of RAP concrete

Durability property	Summary	Reference
Permeability	Measures resistance to water and liquid penetration. Evaluates moisture ingress and potential for deterioration.	[31, 32]
Freeze-thaw resistance	Assesses ability to withstand freezing and thawing cycles. Determines resistance to damage and structural integrity.	[31, 33]
Chloride ion penetration	Evaluates resistance to chloride ingress. Determines potential for corrosion-related issues in chloride-rich environments.	[31, 34]
Factors influencing results	Considers RAP content, aggregate quality, mix design, curing conditions, and exposure conditions.	[35–37]

RAP: Reclaimed asphalt pavement.

evaluation is essential for concrete structures exposed to chloride-rich environments. Tests such as RCPT and chloride migration tests measure RAP concrete's ability to resist chloride ion ingress, crucial for mitigating corrosion-related issues in coastal regions or areas with deicing salts [34].

Several factors influence the outcomes of durability property evaluations, including the RAP content percentage, quality, and gradation of RAP aggregates, mix design parameters, curing conditions, and exposure conditions. Long-term durability assessments through accelerated aging tests and field exposure studies provide a comprehensive understanding of RAP concrete's performance under real-world conditions [35].

By assessing properties like permeability, freeze-thaw resistance, and chloride ion penetration, researchers can optimize mix designs, enhance concrete structure long-term performance, and support sustainable construction by reducing the environmental impact associated with traditional aggregates [36]. Furthermore, this understanding aids in the development of guidelines and specifications for RAP concrete use in diverse applications, empowering engineers and practitioners to make informed decisions considering

exposure conditions, service life requirements, and sustainability goals [37]. Table 3 presents a comprehensive overview of the durability properties of RAP concrete. This table offers valuable insights into the ability of RAP concrete to withstand various environmental conditions, chemical attacks, and long-term deterioration.

Testing Methods and Standards for Evaluating RAP in Concrete

Evaluation of RAP as coarse aggregates in concrete necessitates standardized testing methods and adherence to established standards for reliable and comparable results [38]. Mechanical properties, including compressive, tensile, and flexural strengths, are assessed to gauge the structural integrity of RAP concrete [39, 40]. Durability properties are equally crucial, with tests such as water permeability, freeze-thaw resistance, and chloride ion penetration evaluating aspects like water ingress resistance, resistance to freeze-thaw cycles, and chloride resistance [41]. Specific testing methods for RAP, focusing on properties like gradation, asphalt content, and binder characteristics, offer insights into the quality of RAP aggregates and binder, impacting RAP concrete performance [42].

Table 4. Concrete mix design incorporating RAP

Aspect	Summary	Reference
Aggregate proportions	Determine optimal blend of RAP and conventional aggregates. Consider RAP particle size distribution for achieving balanced mix.	[48, 50]
Binder selection	Select appropriate cementitious materials based on desired properties. Adjust water demand and workability due to RAP aggregates.	[48, 51]
Water-to-cement ratio and workability	Adjust water content or use water-reducing admixtures to maintain workability. Consider absorptive nature of RAP aggregates.	[48, 52]
Sustainability considerations	Reduce the need for virgin aggregates, promote recycling, and decrease environmental impact. Contribute to sustainability goals.	[48, 53]
Admixture usage	Consider dosage and type of chemical admixtures to enhance workability, strength, and durability. Ensure compatibility with RAP mix.	[48, 54]
Laboratory testing	Conduct tests on fresh and hardened concrete to validate mix design. Evaluate workability, strength, and durability characteristics.	[48, 55]

RAP: Reclaimed asphalt pavement.

To ensure test result consistency and comparability, established standards and guidelines from organizations like ASTM, EN, and national standards bodies are followed, with standards such as ASTM C39, C496, C78, C1202, C666, and NT BUILD 492 widely recognized for concrete testing and ASTM D6307, D6925, and D7175 for RAP properties testing [43, 44]. The use of standardized testing methods and compliance with these standards enhance the precision, reliability, and comparability of results in RAP concrete evaluation, fostering data sharing and well-informed decision-making [45]. Such practices also bolster the credibility and acceptance of RAP concrete in construction, promoting its sustainable use and supporting standardized procedures in the industry [46, 47].

Concrete Mix Design Incorporating RAP

Concrete mix design for RAP incorporation involves key considerations such as aggregate proportions, binders, water-to-cement ratio, and sustainability [48]. Evaluating RAP gradation, typically different from conventional aggregates, and performing sieve analyses are essential for balanced mixing and improved mechanical properties [49, 50]. The choice and dosage of cementitious materials must align with desired concrete properties and workability [51]. RAP's absorptive nature can impact the water demand, necessitating adjustments like increased water content or water-reducing admixtures for maintaining workability [52]. RAP's use contributes to sustainability by reducing the need for virgin aggregates, conserving resources, and promoting recycling [53]. Considering the dosage and compatibility of chemical admixtures further enhances the mix's performance and durability [54]. Rigorous laboratory testing is vital for confirming the fresh and hardened properties, including workability and strength [55]. Proper mix design optimizes RAP concrete for mechanical properties, durability, and sustainability, aligning with industry goals [56]. Table 4 provides a detailed summary of concrete mix designs that incorporate RAP as coarse aggregates.

Performance Testing and Evaluation Methods

Performance testing of RAP in concrete is essential to evaluate its quality and suitability for construction [57]. Mechanical properties like compressive, tensile, and flexural strength assess the load-bearing capacity of RAP concrete [57, 58]. Durability tests, including permeability, freeze-thaw resistance, and chloride ion penetration, evaluate RAP concrete's ability to withstand environmental stressors [59, 60]. Additional tests for shrinkage, creep, abrasion resistance, and impact resistance provide insights into RAP concrete's long-term behavior and application suitability [61, 62]. To ensure reliable and consistent evaluation, standards from organizations like ASTM International and the American Concrete Institute have been established [63]. These tests help engineers and researchers select and optimize RAP concrete mixtures, supporting sustainable and high-performance construction [64]. Table 5 is a comprehensive overview of the performance testing and evaluation methods used for RAP concrete.

Factors Affecting the Performance of RAP in Concrete

Several factors influence the performance of RAP in concrete [65]. Key factors include RAP gradation, which impacts workability, strength, and durability [64]. Asphalt content can affect workability and bonding [65, 66]. Moisture content influences strength and shrinkage [66, 67]. Compatibility with cementitious materials is crucial for proper hydration [67, 68]. Environmental conditions, like temperature and humidity, affect setting and curing [69]. Mix proportions and additives, including water reducers and air entraining agents, impact workability, strength, and freeze-thaw resistance [70]. Construction practices, such as mixing, compaction, and curing, play a vital role [71]. Addressing these factors optimizes RAP's performance in concrete and informs guidelines for sustainable infrastructure solutions [72]. Table 6 presents a summarized overview of the key factors influencing the performance of RAP in concrete construction.

Table 5. Performance testing and evaluation methods for RAP concrete

Testing method	Summary	Reference
Mechanical properties	Evaluate compressive, tensile, and flexural strength of RAP concrete. Assess its load-bearing capacity and structural integrity.	[57, 58]
Durability properties	Assess permeability, freeze-thaw resistance, and chloride ion penetration of RAP concrete. Evaluate its resistance to deterioration.	[57, 59, 60]
Shrinkage and creep testing	Measure the deformation characteristics of RAP concrete over time. Assess its long-term behavior and potential for cracking.	[61]
Abrasion and impact testing	Evaluate the wear resistance and impact resistance of RAP concrete. Assess its suitability for high-traffic areas and dynamic loads.	[62]
Standards and guidelines	Adhere to established standards (e.g., ASTM, ACI) for conducting performance tests on RAP concrete. Ensure reliable evaluation.	[63]

RAP: Reclaimed asphalt pavement.

Table 6. A summary of the factors affecting the performance of RAP in concrete

Factor	Impact	Reference
RAP gradation	Affects workability, strength, and durability of RAP concrete.	[64–66]
Asphalt content	Influences workability and bond strength of RAP concrete.	[65, 66]
Moisture content	Impacts workability, strength, and drying shrinkage of RAP concrete.	[66, 67]
Compatibility with cementitious materials	Affects hydration and strength development of RAP concrete.	[67, 68]
Environmental conditions	Temperature and humidity influence setting time and curing of RAP concrete.	[69]
Mix proportions and additives	Optimal proportions and additives enhance workability and durability of RAP concrete.	[70]
Construction practices	Proper mixing, compaction, and curing techniques ensure desired performance of RAP concrete.	[71]

RAP: Reclaimed asphalt pavement.

Table 7. RAP content and gradation in RAP concrete

Factor	Impact	Reference
RAP content	Influences sustainability, workability, strength, and durability of RAP concrete.	[72]
RAP gradation	Affects workability, mechanical properties, and potential issues in RAP concrete.	[73]
RAP material	Particle size distribution, angularity, and presence of contaminants affect RAP performance.	[74]
Blending process	Proper processing and blending of RAP with other aggregates ensure quality and consistency.	[76]

RAP: Reclaimed asphalt pavement.

11.0 RAP Content and Gradation

In concrete construction using RAP as coarse aggregates, the RAP content and gradation are pivotal factors influencing RAP concrete's performance and properties. RAP content refers to the percentage of RAP used in the aggregate mix. While higher RAP content offers sustainability benefits by reducing environmental impact and conserving resources, it must be carefully balanced to avoid drawbacks like reduced workability, lower strength, and durability concerns. The optimum RAP content varies depending on RAP quality, desired concrete performance, and project specifics [72].

RAP's particle size distribution significantly impacts workability, mechanical properties, and overall performance of RAP concrete. Proper gradation ensures compatibility with other aggregates used in the mix. Well-graded RAP aggregates

optimize particle packing, improving mechanical properties and durability while mitigating issues like excessive voids, poor workability, and segregation or bleeding [73].

Balancing RAP content and gradation is crucial for a well-optimized concrete mix. Engineers should understand RAP characteristics and conduct thorough laboratory testing to determine the appropriate RAP content and adjust gradation for desired concrete performance [75]. The selection and blending of RAP with other aggregates must adhere to standards and guidelines for consistent concrete quality. This optimization, considering parameters like cement content, water-to-cement ratio, and supplementary materials, balances sustainability goals, concrete performance, and code compliance [77]. Table 7 provides a detailed summary of the RAP content and gradation in RAP concrete.

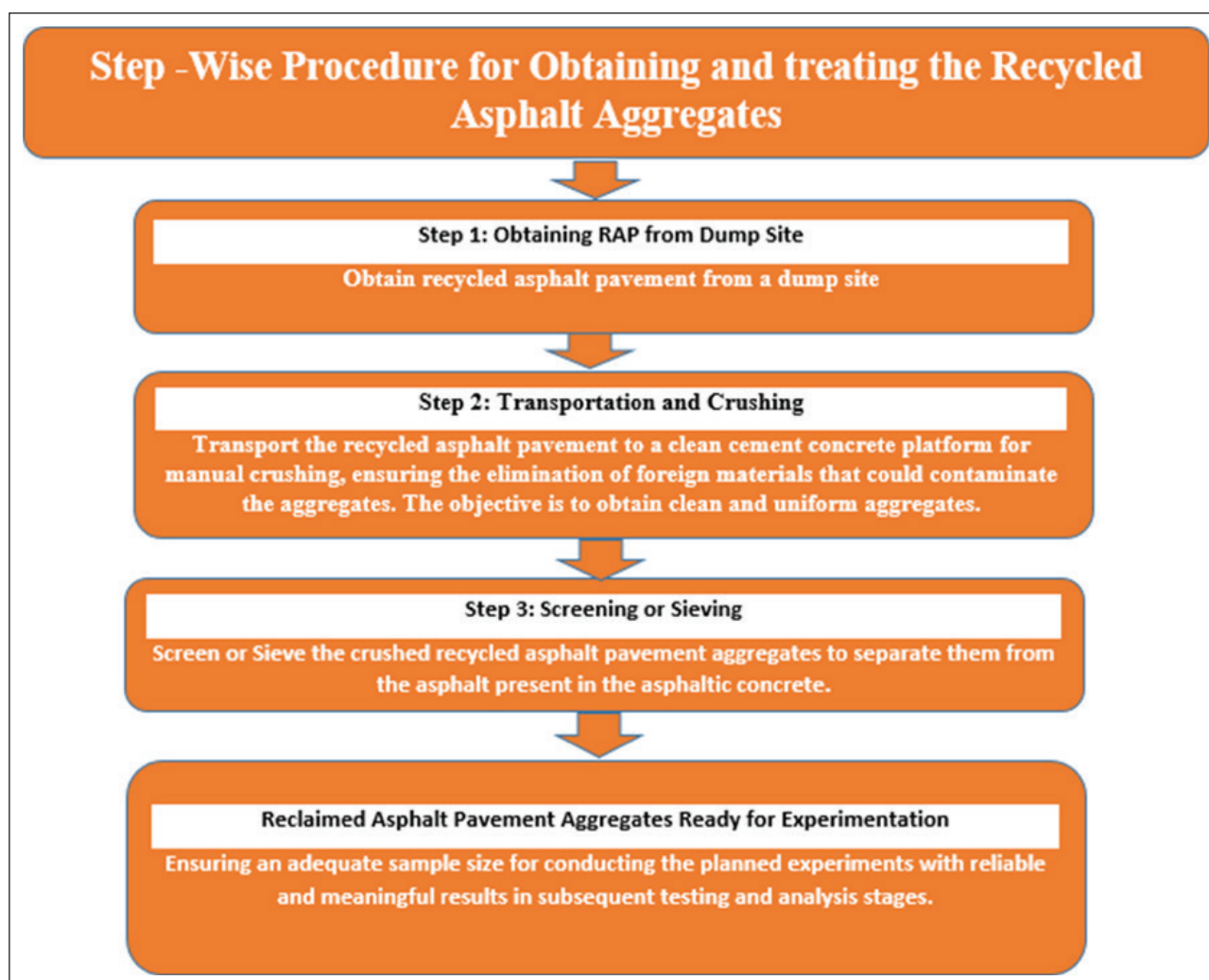


Figure 3. A typical procedure for processing RAP.

Processing Techniques

Processing techniques are vital for preparing RAP for use in concrete construction, enhancing the quality and performance of RAP concrete. The first step is crushing, which reduces the asphalt material to the appropriate aggregate size. Primary and secondary crushers are utilized for this purpose. Proper crushing ensures the desired particle size distribution, a crucial factor for concrete performance [78].

Following crushing, the RAP material undergoes screening to separate aggregates into different size fractions. This step, done through vibrating screens or sieves, eliminates oversized particles and ensures compliance with gradation requirements. Screening also removes any remaining fine particles that could impact concrete workability and performance [80].

Blending is the next step, where RAP aggregates are mixed with other conventional aggregates to create a well-graded and homogeneous mixture. This process balances particle size distribution and enhances concrete quality and performance. It involves careful proportioning based on gradation, particle shape, and specific properties. Properly adhering to industry best practices, standards, and maintaining equipment ensures consistent and accurate processing [81].

Figure 3 illustrates a typical procedure for processing RAP. This procedure outlines the sequential steps involved in the processing of RAP materials, providing a visual guide to the key stages in the recycling process.

Addressing potential contaminants in RAP material is crucial. Contaminants like residual asphalt or foreign materials can harm RAP concrete properties and performance [82]. Therefore, processing methods must include measures like thermal or solvent extraction to remove or reduce contaminants [83].

Utilizing suitable processing techniques such as crushing, screening, and blending is key to optimizing RAP aggregate quality. These techniques ensure proper sizing, contaminant removal, and integration with other aggregates, yielding durable, sustainable, high-performance RAP concrete [84]. Table 8 provides a comprehensive overview of the various processing techniques used for Reclaimed Asphalt Pavement (RAP) in concrete construction.

Admixtures and Additives

Admixtures and additives are vital components in concrete, even more so when incorporating RAP as coarse

Table 8. Processing techniques for RAP in concrete construction

Technique	Purpose	Reference
Crushing	Reduces RAP material to suitable aggregate size for concrete production.	[79]
Screening	Separates RAP aggregates into desired size fractions and removes impurities.	[80]
Blending	Combines RAP aggregates with other aggregates for a well-graded mixture.	[81]
Contaminant removal	Addresses potential contaminants through extraction methods.	[83]

RAP: Reclaimed asphalt pavement.

Table 9. Admixtures and additives for RAP concrete construction

Admixture/additive	Purpose	Reference
Water reducing	Reduces water content while maintaining workability	[84]
Set retarding	Delays concrete setting time for extended workability	[85]
Pozzolan	Enhances strength, durability, and chemical resistance	[86]
Air-entraining	Introduces air bubbles for improved freeze-thaw resistance	[87]
Fiber reinforcement	Enhances toughness, impact resistance, and crack resistance	[89]

RAP: Reclaimed asphalt pavement.

aggregates [84]. Water Reducing Admixtures, also known as plasticizers or superplasticizers, cut water content while maintaining workability. They disperse cement particles effectively, enhancing fluidity for better flow and consolidation, which is particularly useful for RAP concrete by improving cohesion and bonding between RAP aggregates and the cement matrix [85]. Set Retarding Admixtures, or set retarders, delay concrete setting, beneficial when extended workability or delayed setting is necessary, such as in hot weather or long transportation times. They provide extra time for proper placement and compaction in RAP concrete, ensuring optimal consolidation and bonding [86]. Pozzolan Admixtures, like fly ash or silica fume, react with cement hydration byproducts to enhance strength, durability, and chemical resistance. When used in RAP concrete, they compensate for any deficiencies in the cementitious properties of RAP aggregates, improving the overall mixture [87]. Air-Entraining Admixtures introduce stable air bubbles, improving freeze-thaw resistance. In RAP concrete, they mitigate potential decreases in freeze-thaw resistance due to aged asphalt binder or higher porosity in RAP aggregates [88]. Fiber Reinforcement with materials like steel or synthetic fibers enhances toughness, impact resistance, and crack resistance. In RAP concrete, it reduces the risk of cracking, improves post-cracking behavior, and enhances overall durability and long-term performance [89]. Proper selection and dosage of these substances are essential to align with project needs, RAP aggregate properties, and desired concrete characteristics. Following manufacturer recommendations, industry guidelines, and conducting testing and trials ensures effective incorporation and compatibility within the RAP concrete mixture for desired properties and performance [90]. Table 9 presents an extensive summary of the various admixtures and additives used in RAP concrete construction.

Curing Conditions and Environmental Factors

Curing conditions and environmental factors are pivotal in optimizing concrete performance when RAP is used as coarse aggregates [90, 91]. Maintaining the right moisture and temperature levels during curing is vital for cement hydration and strength development. In RAP concrete, aged asphalt binder in RAP aggregates may affect moisture characteristics, necessitating tailored curing approaches [92]. Curing duration significantly impacts concrete strength and durability. Longer curing periods foster continued hydration and more durable cementitious products, which is especially beneficial in RAP concrete, improving mechanical and durability properties [92, 93].

Various curing methods are available for RAP concrete, such as moist curing, membrane curing, and curing compounds, each with its advantages [94, 95]. The choice depends on project needs, desired properties, and the influence of aged asphalt binder in RAP aggregates. Environmental conditions, including temperature, humidity, and exposure to external elements, influence the curing process and RAP concrete's performance [95]. Adapting mix proportions and curing methods to suit environmental conditions is essential to ensure optimal performance [96].

By carefully managing curing conditions and considering environmental factors, RAP concrete's performance can be enhanced, ensuring the development of strength, durability, and longevity. Adhering to industry standards and practices, customized for RAP concrete's unique characteristics and project requirements, is crucial for achieving desired performance under various environmental conditions [90]. Regular monitoring and quality control throughout the curing process are recommended [91]. Table 10 presents an extensive summary of the various admixtures and additives used in RAP concrete construction.

Table 10. Curing conditions and environmental factors for RAP concrete

Aspect	Importance	Reference
Moisture and temperature	Critical for hydration and reactivity, affects strength and durability	[91]
Curing duration	Influences strength and durability development, longer curing improves properties	[92]
Curing methods	Various methods include moist curing, membrane curing, and curing compounds	[95]
Environmental factors	Temperature, humidity, and exposure affect curing and concrete performance	[95]

RAP: Reclaimed asphalt pavement.

Table 11. A summary of the future research directions and recommendations for RAP concrete

Research direction	Recommendations
Long-term performance assessment	Conduct studies to evaluate durability and performance of RAP concrete under various environmental and loading conditions
Optimal RAP content and gradation	Investigate the influence of RAP content and gradation on mechanical and durability properties of concrete
Mix design optimization	Develop improved mix design methods and guidelines tailored for RAP concrete, considering RAP characteristics and properties
Performance evaluation under dynamic loading	Study behavior of RAP concrete under dynamic loading conditions and develop design guidelines for high-stress applications
Environmental impact assessment	Conduct life cycle assessments to evaluate environmental impact and carbon dioxide sequestration potential of RAP concrete
Cost-effectiveness analysis	Perform cost-effectiveness analyses to assess the economic feasibility and advantages of using RAP in concrete construction
Standardization and guidelines	Develop standardized testing methods, specifications, and guidelines specific to RAP concrete to facilitate quality control and implementation

RAP: Reclaimed asphalt pavement.

Research Gap

In the assessment of RAP within concrete construction, several research gaps have been identified that warrant attention. Firstly, there is a notable lack of long-term studies to evaluate how RAP concrete performs over extended durations, which is crucial for understanding its durability under various environmental conditions. Furthermore, more comprehensive research is needed to explore the influence of diverse environmental factors, such as varying climates and exposure to harsh chemicals, on RAP concrete. Investigating the fundamental mechanisms underlying RAP concrete's performance is another critical gap, with a focus on the interaction between RAP aggregates and the cementitious matrix. Additionally, the scalability of RAP concrete to large construction projects, like highways and bridges, requires further investigation. Standardized testing methods and protocols for RAP concrete remain underdeveloped, limiting consistency and comparability across studies. Moreover, a comprehensive economic assessment, including life cycle cost analysis, is needed to determine the economic viability of RAP concrete. Lastly, the integration of RAP concrete into design codes and guidelines necessitates further research to ensure its safe and efficient incorporation into construction practices. Addressing these research gaps will advance our knowledge and promote sustainable construction practices.

CONCLUSION

This comprehensive literature review explores the performance of RAP when used as coarse aggregates in concrete construction. It covers a wide range of aspects, including mechanical properties, durability, testing methods, mix design, performance evaluation, influencing factors, RAP content, gradation, processing techniques, admixtures, curing, and environmental considerations. Assessing RAP's performance in concrete construction is crucial due to its potential to enhance sustainability by reducing natural aggregate consumption, recycling waste materials, and decreasing the carbon footprint of construction projects. It not only offers cost savings but also improves the mechanical and durability properties of concrete, representing a significant advancement in construction practices.

Further research is necessary to address identified gaps, such as conducting long-term studies, understanding specific environmental influences, elucidating the underlying mechanisms, exploring large-scale applications, establishing standardized testing methods, and assessing the economic feasibility. The integration of RAP into design codes and specifications must also be pursued to ensure its safe and efficient adoption, furthering the construction industry's transition toward environmentally conscious and economically viable practices.

Future Research Directions and Recommendations

Future research on RAP in concrete construction should emphasize long-term performance assessments under varying environmental conditions, optimal RAP content and gradation, mix design improvements tailored for RAP, and evaluating RAP concrete's behavior under dynamic loading conditions. Additionally, assessing the environmental impact and cost-effectiveness of RAP concrete is essential for its broader adoption. Developing standardized testing methods, specifications, and guidelines specific to RAP concrete is crucial for consistent evaluation and quality control in construction projects, facilitating its widespread acceptance and utilization. These research directions provide valuable guidance for further exploration in this field, promoting more sustainable and eco-friendly infrastructure practices. Table 11 summarizes these future research directions and recommendations for RAP concrete, offering a concise reference for researchers and professionals seeking to advance the knowledge and application of RAP in concrete construction.

ACKNOWLEDGMENTS

Deep gratitude to Engr. Prof. Jonah C. Agunwamba for being an exceptional academic model, whose dedication and expertise have greatly influenced and inspired many students.

DATA AVAILABILITY STATEMENT

The author confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

REFERENCES

- [1] F. Palise, "Performance Evaluation of Reclaimed Asphalt Pavement (RAP) as a Dense Graded Aggregate Base Course (DGABC)," 1994.
- [2] M. Wu, "Evaluation of High Percentage Recycled Asphalt Pavement as Base Course Materials," 2011.
- [3] D. Jua, "An Evaluation of Heated Reclaimed Asphalt Pavement (RAP) Material and Wax Modified Asphalt for Use in Recycled Hot Mix Asphalt (HMA)," 2007.
- [4] A. K. Mukhopadhyay and X. Shi, "Validation of RAP And/or RAS in Hydraulic Cement Concrete," 2017.
- [5] K. Babaei, "Evaluation of the Performance of Cold-Mix Recycled Asphalt Concrete Pavement in Washington," 1989.
- [6] C. L. Monismith, R. B. Leahy, and J. A. Epps, "Asphalt Paving Technology," McGraw-Hill Companies, 1997.
- [7] A. Gomes Correia, M. G. Winter, and A. J. Puppala, "A review of sustainable approaches in transport infrastructure geotechnics," *Transportation Geotechnics*, Vol. 7, pp. 21–28, 2016. [\[CrossRef\]](#)
- [8] F. G. Praticò, R. Vaiana, and M. Giunta, "Pavement Sustainability: Permeable Wearing Courses by Recycling Porous European Mixes," *Journal of Architectural Engineering*, Vol. 19(3), pp. 186–192, 2013. [\[CrossRef\]](#)
- [9] Y. Qiao, A. R. Dawson, T. Parry, G. Flintsch, and W. Wang, "Flexible Pavements and Climate Change: A Comprehensive Review and Implications," *Sustainability*, Vol. 12(3), 2020. [\[CrossRef\]](#)
- [10] S. Bressi, A. G. Dumont, and M. N. Partl, "A new laboratory methodology for optimization of mixture design of asphalt concrete containing reclaimed asphalt pavement material," *Materials and Structures*, Vol. 49(12), pp. 4975–4990, 2016. [\[CrossRef\]](#)
- [11] B. T. Cox, and I. L. Howard, "Cold In-Place Recycling Characterization for Single-Component or Multiple-Component Binder Systems," 2016. [\[CrossRef\]](#)
- [12] C. Villiers, Y. Mehta, M. Tia, R. Roque, and B. Dietrich, "The importance of mineral filler on construction specifications," *International Journal of Pavement Engineering*, Vol. 9(5), pp. 343–353, 2008. [\[CrossRef\]](#)
- [13] B. T. Cox and I. L. Howard, "Merits of Asphalt Concrete Durability and Performance Tests When Applied to Cold In-Place Recycling," 2015. [\[CrossRef\]](#)
- [14] M. Berry, J. Stephens, and B. Bermel, "Feasibility of Reclaimed Asphalt Pavement as Aggregate in Portland Cement Concrete," 2013.
- [15] C. Raab, "Proceedings of the 9th International Conference on Maintenance and Rehabilitation of Pavements--Mairepav9," Springer, 2020. [\[CrossRef\]](#)
- [16] S. Amziane, F. Collet, and Springerlink (Online Service), "Bio-Aggregates Based Building Materials: State-of-The-Art Report of the RILEM Technical Committee 236--BBM," Springer Netherlands, 2017. [\[CrossRef\]](#)
- [17] A. Mohammadinia, A. Arulrajah, J. Sanjayan, M. M. Disfani, M. W. Bo, and S. Darmawan, "Laboratory evaluation of the use of cement-treated construction and demolition materials in pavement base and subbase applications," *Journal of Materials in Civil Engineering*, 27(6), Article 04014186, 2015.
- [18] M. Tao, and R. B. Mallick, "Effects of warm-mix asphalt additives on workability and mechanical properties of reclaimed asphalt pavement material," *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2126(1), pp. 151–160, 2009. [\[CrossRef\]](#)
- [19] J. Montañez, S. Caro, D. Carrizosa, A. Calvo, and X. Sánchez, "Variability of the mechanical properties of Reclaimed Asphalt Pavement (RAP) obtained from different sources," *Construction and Building Materials*, Vol. 230, Article 116968, 2020. [\[CrossRef\]](#)

- [20] X. Yu, M. Zaumanis, S. dos Santos, and L. D. Poulikakos, "Rheological, microscopic, and chemical characterization of the rejuvenating effect on asphalt binders," *Fuel*, Vol. 135, pp. 162–171, 2014. [\[CrossRef\]](#)
- [21] A. Behnood, "Application of rejuvenators to improve the rheological and mechanical properties of asphalt binders and mixtures: A review," *Journal of Cleaner Production*, Vol. 231, pp. 171–182, 2019. [\[CrossRef\]](#)
- [22] G. Valdés, F. Pérez-Jiménez, R. Miró, A. Martínez, and R. Botella, "Experimental study of recycled asphalt mixtures with high percentages of reclaimed asphalt pavement (RAP)," *Construction and Building Materials*, Vol. 25(3), pp. 1289–1297, 2011. [\[CrossRef\]](#)
- [23] L. D. Poulikakos, S. dos Santos, M. Bueno, S. Kuentzel, M. Hugener, and M. N. Partl, "Influence of short and long term aging on chemical, microstructural and macro-mechanical properties of recycled asphalt mixtures," *Construction and Building Materials*, Vol. 51, pp. 414–423, 2014. [\[CrossRef\]](#)
- [24] C. Plati, M. Tsakoumaki, and K. Gkyrtis, "Physical and Mechanical Properties of Reclaimed Asphalt Pavement (RAP) Incorporated into Unbound Pavement Layers," *Applied Sciences*, vol. 13(1), Article 362, 2022. [\[CrossRef\]](#)
- [25] M. C. Cavalli, M. Zaumanis, E. Mazza, M. N. Partl, and L. D. Poulikakos, "Effect of ageing on the mechanical and chemical properties of binder from RAP treated with bio-based rejuvenators," *Composites Part B-engineering*, Vol. 141, pp. 174–181, 2018. [\[CrossRef\]](#)
- [26] I. Widyatmoko, "Mechanistic-empirical mixture design for hot mix asphalt pavement recycling," *Construction and Building Materials*, Vol. 22(2), pp. 77–87, 2008. [\[CrossRef\]](#)
- [27] S. W. Goh, and Z. You, "Mechanical Properties of Porous Asphalt Pavement Materials with Warm Mix Asphalt and RAP," *Journal of Transportation Engineering*, vol. 138(1), pp. 90–97, 2012. [\[CrossRef\]](#)
- [28] M. Ameri, and A. Behnood, "Laboratory studies to investigate the properties of CIR mixes containing steel slag as a substitute for virgin aggregates," *Construction and Building Materials*, Vol. 26(1), pp. 475–480, 2012. [\[CrossRef\]](#)
- [29] S. N. Nahar, M. Mohajeri, A. J. M. Schmets, A. Scarpas, M. F. C. van de Ven, and G. Schitter, "First observation of blending-zone morphology at interface of reclaimed asphalt binder and virgin bitumen," *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2370(1), pp. 1–9, 2013. [\[CrossRef\]](#)
- [30] M. Fakhri and E. Amoosoltani, "The effect of Reclaimed Asphalt Pavement and crumb rubber on mechanical properties of Roller Compacted Concrete Pavement," *Construction and Building Materials*, Vol. 137, pp. 470–484, 2017. [\[CrossRef\]](#)
- [31] H. M. R. D. Silva, J. R. M. Oliveira, and C. M. G. Jesus, "Are totally recycled hot mix asphalts a sustainable alternative for road paving?" *Resources, Conservation and Recycling*, Vol. 60, pp. 38–48, 2012. [\[CrossRef\]](#)
- [32] I. Widyatmoko, "Mechanistic-empirical mixture design for hot mix asphalt pavement recycling," *Construction and Building Materials*, Vol. 22(2), pp. 77–87, 2008. [\[CrossRef\]](#)
- [33] Z. Leng, A. Sreeram, R. K. Padhan, Z. Tan, "Value-added application of waste PET based additives in bituminous mixtures containing high percentage of reclaimed asphalt pavement (RAP)," *Journal of Cleaner Production*, Vol. 196, pp. 615–625, 2018. [\[CrossRef\]](#)
- [34] S. Im, F. Zhou, R. Lee, and T. Scullion, "Impacts of rejuvenators on performance and engineering properties of asphalt mixtures containing recycled materials," *Construction and Building Materials*, Vol. 53, pp. 596–603, 2014. [\[CrossRef\]](#)
- [35] M. Elkashef and R. C. Williams, "Improving fatigue and low temperature performance of 100% RAP mixtures using a soybean-derived rejuvenator," *Construction and Building Materials*, Vol. 151, pp. 345–352, 2017. [\[CrossRef\]](#)
- [36] S. Singh, G. D. Ransinchung, and P. Kumar, "An economical processing technique to improve RAP inclusive concrete properties," *Construction and Building Materials*, Vol. 148, pp. 734–747, 2017. [\[CrossRef\]](#)
- [37] A. Mohammadinia, A. Arulrajah, S. Horpibulsuk, and A. Chinkulkijniwat, "Effect of fly ash on properties of crushed brick and reclaimed asphalt in pavement base/subbase applications," *Journal of Hazardous Materials*, Vol. 321, pp. 547–556, 2017. [\[CrossRef\]](#)
- [38] F. Yin, F. Kaseer, E. Arámbula-Mercado, and A. Epps Martin, "Characterising the long-term rejuvenating effectiveness of recycling agents on asphalt blends and mixtures with high RAP and RAS contents," *Road Materials and Pavement Design*, Vol. 18(Supp 4), pp. 273–292, 2017. [\[CrossRef\]](#)
- [39] S. Guthrie, D. A. Cooley, and D. L. Eggett, "Effects of reclaimed asphalt pavement on mechanical properties of base materials," *Sage*, Vol. 2005(1), pp. 44–52, 2007. [\[CrossRef\]](#)
- [40] S. Debbarma, M. Selvam, and S. Singh, "Can flexible pavements' waste (RAP) be utilized in cement concrete pavements? – A critical review," *Construction and Building Materials*, Vol. 259, Article 120417, 2020. [\[CrossRef\]](#)
- [41] B. J. Kwon, D. Kim, S. K. Rhee, and Y. R. Kim, "Spray injection patching for pothole repair using 100 percent reclaimed asphalt pavement," *Construction and Building Materials*, Vol. 166, pp. 445–451, 2018. [\[CrossRef\]](#)
- [42] R. C. West, J. R. Willis, and M. O. Marasteanu, "Improved mix design, evaluation, and materials management practices for hot mix asphalt with high reclaimed asphalt pavement content," *Transportation Research Board*, 2013.
- [43] R. F. Bonaquist, National Cooperative Highway Research Program, National Research Council (U.S.). *Transportation Research Board*, American Association

- tion Of State Highway And Transportation Officials, Advanced Asphalt Technologies, Llc, United States. Federal Highway Administration, "Mix Design Practices for Warm Mix Asphalt," Transportation Research Board, 2011. [\[CrossRef\]](#)
- [44] Zofka, National Research Council (U.S.). Transportation Research Board, Second Strategic Highway Research Program (U.S.), "Evaluating Applications of Field Spectroscopy Devices to Fingerprint Commonly Used Construction Materials," Transportation Research Board, 2013. [\[CrossRef\]](#)
- [45] Z. You, Q. Dai, and F. Xiao, "Advanced Asphalt Materials and Paving Technologies," MDPI, 2018. [\[CrossRef\]](#)
- [46] R. McDaniel, "Recommended use of reclaimed asphalt pavement in the superpave mix design method," 2001.
- [47] N. Sabahfar, "Use of high-volume reclaimed asphalt pavement (rap) for asphalt pavement rehabilitation," 2012.
- [48] Asphalt Institute, "Superpave Mix Design," Asphalt Institute, 2001.
- [49] H. "David" Lee, C. Van Winkle, and R. Carlson, "Development of Quality Standards for Inclusion of High Recycled Asphalt Pavement Content in Asphalt Mixtures," 2015.
- [50] P. Chavez, "Impact of Reclaimed Asphalt Pavement in Asphalt Concrete Mixes Used for Airfield Pavement," 2016.
- [51] M. N. Partl, L. Porot, H. Di Benedetto, F. Canestrari, P. Marsac, and G. Tebaldi, "Testing and Characterization of Sustainable Innovative Bituminous Materials and Systems: State-of-The-Art Report of the RILEM Technical Committee 237-SIB," Springer, 2018. [\[CrossRef\]](#)
- [52] A. Arulrajah, J. Piratheepan, M. M. Disfani, and M. W. Bo, "Geotechnical and geoenvironmental properties of recycled construction and demolition materials in pavement subbase applications," *Journal of Materials in Civil Engineering*, Vol. 25(8), pp. 1077–1088, 2013.
- [53] M. T. Tiza, "Effect of Thermal Variances on Flexible Pavements," *Journal of Sustainable Construction Materials and Technologies*, Vol. 7(3), pp. 220–230, 2022. [\[CrossRef\]](#)
- [54] T. Edil, "Monitoring and Evaluation of Fly Ash Stabilization Stabilized Subgrade Constructed by the WisDOT," 2010.
- [55] D. H. Timm, B. K. Diefenderfer, and B. F. Bowers, "Cold central plant recycled asphalt pavements in high traffic applications," *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2672(40), pp. 291–303, 2018.
- [56] J. D. Doyle, "Characterization of Reclaimed Asphalt and Performance Based Evaluation of Its Use in Recycled Mixtures," 2011.
- [57] M. T. Tiza, "Integrating Sustainability into Civil Engineering and the Construction Industry," *Journal of Cement Based Composites*, Vol. 4(1), pp. 1–11, 2023. [\[CrossRef\]](#)
- [58] H. Ye, "Innovative Evaluation of Recycled Asphalt Pavement (Rap) Use in Slurry Seal Applications," 2021.
- [59] M. N. Partl, L. Porot, H. Di Benedetto, F. Canestrari, P. Marsac, and G. Tebaldi, "Testing and Characterization of Sustainable Innovative Bituminous Materials and Systems: State-of-The-Art Report of the RILEM Technical Committee 237-SIB," Springer, 2018. [\[CrossRef\]](#)
- [60] M. Tiza, "Sustainability in the civil engineering and construction industry: A review," *Journal of Sustainable Construction Materials and Technologies*, Vol. 7(1), pp. 30–39, 2022. [\[CrossRef\]](#)
- [61] M. T. Tiza, K. Jirgba, H. A. Sani, T. Sesugh, "Effect of thermal variances on flexible pavements," *Journal of Sustainable Construction Materials and Technologies*, Vol. 7(3), pp. 220–230, 2022. [\[CrossRef\]](#)
- [62] W. G. Whitcomb, R. G. Hicks, and S. J. Escobar, "Evaluation of a Unified Design for Asphalt Recycling by Means of Dynamic and Fatigue Testing," 1981.
- [63] S. Erkens, X. Liu, A. Kumar, Y. Tan, "Functional Pavement Design," CRC Press, 2016. [\[CrossRef\]](#)
- [64] P. Pathak, and P. R. Rout, "Urban Mining for Waste Management and Resource Recovery," CRC Press, 2021. [\[CrossRef\]](#)
- [65] G. R. Woolley, J. J. M. Goumans, P. J. Wainwright, "Waste Materials in Construction," Elsevier, 2000.
- [66] X. D. Zhang, B. Zhang, L. Z. Jiang, M. W. Xie, "Civil, Structural and Environmental Engineering," Trans Tech Publications Ltd, 2013. [\[CrossRef\]](#)
- [67] P. H. Emmons, and A. M. Vaysburd, "Performance Criteria for Concrete Repair Materials," 1995.
- [68] J. T. John, United States. Federal Highway Administration, Iowa State University. National Concrete Pavement Technology Center, "Sustainable Concrete Pavements: A Manual of Practice," National Concrete Pavement Technology Center, Iowa State University, 2012.
- [69] A. Kumar, A. T. Bhasin, A. T. Papagiannakis, and D. Little, "Advances in Materials and Pavement Prediction II Contributions to the 2nd International Conference on Advances in Materials and Pavement Performance Prediction (AM3P 2020), 27–29 May 2020, San Antonio, TX, USA," CRC Press, 2020. [\[CrossRef\]](#)
- [70] N. J. Delatte, "Concrete pavement design, construction, and performance," CRC Press, 2014. [\[CrossRef\]](#)
- [71] Nikolaides, "Highway engineering," CRC Press, 2014. [\[CrossRef\]](#)
- [72] K. R. Reddy, R. K. Pancharathi, N. G. Reddy, S. R. Arukala, "Advances in Sustainable Materials and Resilient Infrastructure," Springer, 2022. [\[CrossRef\]](#)
- [73] M. Arshad, and M. F. Ahmed, "Potential use of reclaimed asphalt pavement and recycled concrete aggregate in base/subbase layers of flexible pave-

- ments,” *Construction and Building Materials*, Vol. 151, pp. 83–97.
- [74] M. T. Tiza, O. Mogbo, S. K. Singh, N. Shaik, and M. P. Shettar, “Bituminous pavement sustainability improvement strategies,” *Energy Nexus*, Vol. 6, 2022. [\[CrossRef\]](#)
- [75] T. Michael, “Characterization of reclaimed asphalt pavement and optimization in polymer modified asphalt blends: A review,” *CEBEL*, Vol. 2(2), pp. 27–34, 2021. [\[CrossRef\]](#)
- [76] Z. You, J. Mills-Beale, E. Fini, S. W. Goh, and B. Colbert, “Evaluation of low-temperature binder properties of warm-mix asphalt, extracted and recovered RAP and RAS, and bioasphalt,” *Journal of Materials in Civil Engineering*, Vol. 23(11), pp. 1569–1574, 2011. [\[CrossRef\]](#)
- [77] L. R. Hoyos, A. J. Puppala, C. A. Ordonez, “Characterization of cement-fiber-treated reclaimed asphalt pavement aggregates: preliminary investigation,” *Journal of Materials in Civil Engineering*, Vol. 23(7), pp. 977–989, 2011. [\[CrossRef\]](#)
- [78] Y. Kim, and H. Lee, “Development of Mix Design Procedure for Cold In-Place Recycling with Foamed Asphalt,” *Journal of Materials in Civil Engineering*, Vol. 18(1), pp. 116–124, 2006. [\[CrossRef\]](#)
- [79] J. Turk, A. Mauko Pranjić, A. Mladenović, Z. Cotić, and P. Jurjavčič, “Environmental comparison of two alternative road pavement rehabilitation techniques: cold-in-place-recycling versus traditional reconstruction,” *Journal of Cleaner Production*, Vol. 121, pp. 45–55, 2016. [\[CrossRef\]](#)
- [80] A. J. Puppala, S. Saride, and R. Williammee, “Sustainable Reuse of Limestone Quarry Fines and RAP in Pavement Base/Subbase Layers,” *Journal of Materials in Civil Engineering*, Vol. 24(4), pp. 418–429, 2012. [\[CrossRef\]](#)
- [81] A. Bonicelli, P. Calvi, G. Martinez-Arguelles, L. Fuentes, and F. Giustozzi, “Experimental study on the use of rejuvenators and plastomeric polymers for improving durability of high RAP content asphalt mixtures,” *Construction and Building Materials*, Vol. 155, pp. 37–44, 2017. [\[CrossRef\]](#)
- [82] D. Lo Presti, K. Vasconcelos, M. Orešković, G. M. Pires, and S. Bressi, “On the degree of binder activity of reclaimed asphalt and degree of blending with recycling agents,” *Road Materials and Pavement Design*, Vol. 21(8), pp. 2071–2090, 2019. [\[CrossRef\]](#)
- [83] R. Ghabchi, D. Singh, and M. Zaman, “Laboratory evaluation of stiffness, low-temperature cracking, rutting, moisture damage, and fatigue performance of WMA mixes,” *Road Materials and Pavement Design*, Vol. 16(2), pp. 334–357, 2015. [\[CrossRef\]](#)
- [84] S. Saride, A. J. Puppala, and R. Williammee, “Assessing recycled/secondary materials as pavement bases,” *Proceedings of the Institution of Civil Engineers - Ground Improvement*, Vol. 163(1), pp. 3–12, 2010. [\[CrossRef\]](#)
- [85] A. Ameli, R. Babagoli, and M. Aghapour, “Laboratory evaluation of the effect of reclaimed asphalt pavement on rutting performance of rubberized asphalt mixtures,” *Petroleum Science and Technology*, Vol. 34(5), pp. 449–453, 2016. [\[CrossRef\]](#)
- [86] S. Adhikari, M. J. Khattak, and B. Adhikari, “Mechanical characteristics of Soil-RAP-Geopolymer mixtures for road base and subbase layers,” *International Journal of Pavement Engineering*, Vol. 21(4), pp. 483–496, 2018. [\[CrossRef\]](#)
- [87] R. Taha, A. Al-Harthy, K. Al-Shamsi, and M. Al-Zubeidi, “Cement Stabilization of Reclaimed Asphalt Pavement Aggregate for Road Bases and Subbases,” *Journal of Materials in Civil Engineering*, Vol. 14(3), pp. 239–245, 2002. [\[CrossRef\]](#)
- [88] A. Mohammadinia, A. Arulrajah, J. Sanjayan, M. M. Disfani, M. W. Bo, and S. Darmawan, “Laboratory evaluation of the use of cement-treated construction and demolition materials in pavement base and subbase applications,” *Journal of Materials in Civil Engineering*, Vol. 27(6), 2015. [\[CrossRef\]](#)
- [89] A. Modarres, and Z. Hosseini, “Mechanical properties of roller compacted concrete containing rice husk ash with original and recycled asphalt pavement material,” *Materials & Design*, Vol. 64, pp. 227–236, 2014. [\[CrossRef\]](#)
- [90] Y. Kim, H. Lee, and M. Heitzman, “Validation of new mix design procedure for cold in-place recycling with foamed asphalt,” *Journal of Materials in Civil Engineering*, Vol. 19(11), pp. 1000–1010, 2007. [\[CrossRef\]](#)
- [91] Yan, W. Huang, and Q. Lv, “Study on bond properties between RAP aggregates and virgin asphalt using Binder Bond Strength test and Fourier Transform Infrared spectroscopy,” *Construction and Building Materials*, Vol. 124, pp. 1–10, 2016. [\[CrossRef\]](#)
- [92] S. Al-Oraimi, F. H. Hassan, and A. Hago, “Recycling of reclaimed asphalt pavement in portland cement concrete,” *The Journal of Engineering Research*, Vol. 6(1), 2009. [\[CrossRef\]](#)
- [93] W. Fedrigo, W. P. Núñez, M. A. Castañeda López, T. R. Kleinert, and J. A. P. Ceratti, “A study on the resilient modulus of cement-treated mixtures of RAP and aggregates using indirect tensile, triaxial and flexural tests,” *Construction and Building Materials*, Vol. 171, 2018. [\[CrossRef\]](#)
- [94] S. Zulakmal, N. A. Aziz, M. M. Khalid, H. M. Zain, M. R. Hainin, and E. A. Oluwasola, “Influence of active filler, curing time and moisture content on the strength properties of emulsion and foamed bitumen stabilized mix,” 2014.
- [95] M. R. Hainin, M. Y. Matori, and O. E. Akin, Evaluation of factors influencing strength of foamed bitumen stabilised mix. *Jurnal Teknologi*, 70(4), 2014.
- [96] Wang, S. Shen, X. Li, and B. Song, “Micro-surfacing mixtures with reclaimed asphalt pavement: Mix design and performance evaluation,” *Construction and Building Materials*, Vol. 201, pp. 303–313, 2019. [\[CrossRef\]](#)



Research Article

Assessment of tube well water quality in selected residential areas in Khulna

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ARTICLE INFO

Article history

Received: 18 September 2023

Revised: 29 October 2023

Accepted: 14 November 2023

Key words:

Khulna residential areas;
Physico-chemical and biological
parameter; Standard limits; Tube
well water quality

ABSTRACT

Clean water is vital for sustainable development, fostering socio-economic growth, ecological stability, and human survival. The study aimed to evaluate the quality of tube well water in specific residential areas of Khulna for drinking purposes, comparing it with the standards of World Health Organization (WHO) and Bangladesh (BD). Twenty tube well water samples were collected from residential areas at depths of 700–1500 ft. The samples were tasted with about 20 parameters, including physical: color, taste, odor, total dissolved solids (TDS) and total suspended solids (TSS); chemical: acidity/alkalinity (pH), arsenic (As), electrical conductivity (EC), dissolved oxygen (DO), bicarbonate (HCO_3^-), calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), chloride (Cl^-), iron (Fe), phosphate (PO_4^{3-}), sulfate (SO_4^{2-}), potassium (K^+); and bacteriological parameters: total coliforms and *E. coli* bacteria. Most of the samples were found to have higher TDS (avg. 1380 mg/L), TSS (avg. 620 mg/L), Fe (avg. 20.2 mg/L), K^+ (avg. 194.1 mg/L), and Na^+ (avg. 439 mg/L) concentrations compared to the WHO and BD Standards. 90 to 95% of samples exhibited acceptable levels of EC, pH, DO, Mg^{2+} , Ca^{2+} , Cl^- , and SO_4^{3-} . The salinity levels in most of the samples were excessive to be used for drinking, and the levels were especially very high in samples S-01 (Na^+ 820 and Cl^- 3195 mg/L) and S-04 (Na^+ 660 and Cl^- 2946 mg/L). The arsenic levels were found to be higher than acceptable limit in S-01 (0.086 mg/L) and S-04 (0.091 mg/L) as well. *E. coli* and other bacteria in a few samples (S-01, 04, 13, 16, 17, 19) were detected.

Cite this article as: Tabassum S, Dristy JT, Ahmed A, Riyadh RH. Assessment of tube well water quality in selected residential areas in Khulna. Environ Res Tec 2024;7(1)41–60.

INTRODUCTION

Water plays a crucial role in the natural environment [1, 2], as it supports economic growth, guarantees food security, alleviates poverty, maintains ecological functions, and acts as a potentially limiting resource for both humans and other organisms [3–7]. The provision of a sufficient quantity and quality of water is essential in order to meet the grow-

ing needs of households, industries, and agriculture [8, 9]. Water can exhibit characteristics of both a renewable and nonrenewable resource, depending on its usage and rate of depletion. Therefore, it is imperative to prioritize the resolution of water quality issues and the exploration of efficient management approaches in different nations [10–14]. Groundwater serves as the predominant freshwater resource, with a fraction of it originating from rainfall [15],

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[16–18]. On a global scale, the extraction of groundwater for various purposes has had a substantial impact on socio-economic conditions. Approximately one-third of the global population is dependent on groundwater as a primary source of drinking water [19–21].

Trace amounts of soluble salts can always be found in groundwater. However, groundwater is unfit for agricultural use due to the lack of treatment in municipal sewage generated from decomposable solid waste [22–24], medical waste [25], and other sources, as well as unregulated industrial and agricultural practices. When this sewage infiltrates the ground, it can introduce harmful substances into the groundwater, making it unsuitable for irrigation. Degradation of the drinking water supply can occur if a combination of landfill leachate and wastewater contaminates groundwater sources [26, 27] and introduces harmful pollutants [28–31]. Further, people have reason to be concerned about the safety of groundwater due to the presence of harmful contaminants like pesticides, arsenic, nitrate, fluoride [32], mineral hardness, and iron [33]. In developing countries, 80% of illnesses and 30% of infant mortality rates have been linked to contaminated groundwater [34]. Modifications in the quality of groundwater arise from the interactions between water and rock, along with oxidation-reduction reactions that take place as water infiltrates through the aquifer system [35]. Shallow aquifers are deteriorating as a result of increased population density, extensive human endeavors, insufficient resource utilization, and a lack of efficient management protocols. Deeper aquifers generally have less arsenic contamination. Protecting them from biological and physico-chemical pollutants can be challenging due to their depth and location. Reduced chemical use [36], source protection [37], proper monitoring of contaminants, sustainable farming [38], waste diversion (e.g., biogas production from organic waste [39, 40]), and other measures can prevent groundwater contamination. These reasons may have limited effect on deep aquifers. Contaminants move slowly from the surface to deep aquifers. But persistent environmental contaminants can leach into deep aquifers over time.

Tube well water is generally believed to be devoid of microbial pollution owing to the inherent natural filtration capabilities of the underground environment [41–44]. In the context of Bangladesh, it is observed that a significant proportion of tube wells are situated in suboptimal locations, and their upkeep does not adhere to the sanitary inspection guidelines prescribed by United Nations International Children's Emergency Fund (UNICEF) and WHO [43, 45–48]. A considerable proportion of tube well water in Bangladesh is contaminated with microorganisms, specifically fecal organisms, thereby indicating the presence of contamination [46, 49–55]. Insufficiently constructed sanitary latrines are believed to be among the potential sources of contamination. Waterborne diseases constitute a prominent global health issue [54, 56–59]. The presence of impurities in drinking water possesses the capacity to engender a variety of illnesses, such as cholera, dysentery, typhoid,

hepatitis, and diarrhea. Diarrhea occupies a prominent position within the realm of waterborne illnesses [59, 60–62], as it stands as a primary factor in the mortality of children, it is also estimated that the annual death toll of approximately 25 million individuals by consuming contaminated water [63]. The United Nations (UN) estimates that 2.5 billion people in developing nations lack adequate sanitation, and over half of this population lacks safe drinking water [63]. Groundwater is often referred to as the "hidden sea" due to its vast quantity and concealed nature [64–66]. This obscurity makes groundwater pollution pathways and processes difficult to see. The prioritization of microbial quality control in drinking water should be regarded as a matter of utmost importance for all nations [21, 50, 67–71]. Groundwater holds considerable socioeconomic importance due to its reduced treatment requirements, rendering it a financially viable alternative in comparison to surface water [71].

Coastal areas exhibit a vulnerability to increased levels of salinity in both surface and groundwater [72–76], which is distinguished by the occurrence of total dissolved solids (TDS) [75, 77] and specific chemical components: Cl^- , Na^+ , Mg^{2+} and SO_4^{2-} . The Khulna Division is located in the southwestern coastal region of Bangladesh, where it faces notable difficulties such as salinity in the surrounding area and contamination of shallow aquifers with arsenic. The increase in salinity levels in Khulna can be attributed to the commencement of the Farrakka Barrage operation by India in 1975. The aforementioned development significantly reduced the water discharge of the Ganges River in the surrounding area [78–84]. The Ganges River, known as the Padma in Bangladesh, is situated to the northeast of Khulna city. Currently, the Khulna water supply system is exclusively dependent on groundwater as its primary source. The urban population of Khulna city is experiencing a consistent increase, resulting in an escalating need for water resources. Due to drought, river levels dropping, seawater intrusion during high tides, groundwater contamination, and natural arsenic, Khulna faces severe water scarcity [85, 86]. The evaluation of the origin and quality of groundwater is a vital obligation for the Khulna City Corporation, as the residents of this urban area heavily depend on this resource for their diverse needs.

The purpose of this study is to determine the groundwater (tube well) quality status in terms of various physical, chemical, and bacteriological parameters in different residential areas of Khulna. This research is emphasized because groundwater quality profoundly affects public health and the environment, making it essential for socioeconomic development, effective resource management, and sustainable use. The current research is undertaken due to the limitations of prior studies, which may have had a limited scope, outdated data, insufficient sampling, inadequate assessment of parameters, inconsistent data availability, and changing contamination sources, necessitating a comprehensive and up-to-date evaluation of groundwater quality's multifaceted significance for public health, environmental preservation, socioeconomic development, and resource management.

The primary goals of this study are to conduct a comprehensive evaluation of the deep tube well water quality in different residential regions of Khulna. The ultimate goal is to ensure the provision of safe and sustainable drinking water, while simultaneously protecting public health, the environment, and promoting socioeconomic development. The specific objectives of this study are:

- To evaluate the physical and chemical attributes of tube well water and compare them to the drinking water standards established by both Bangladesh and the WHO.
- To assess the biological conditions of the studied tube well water.

MATERIALS AND METHODS

Study Area

Khulna is situated in the south-western region of Bangladesh, adjacent to the Rupsha and Bhairab Rivers. The location is positioned within the geographical coordinates of 21.38° to 23.15° north latitude and 89.54° east longitude, with an elevation of approximately 30 feet above mean sea level. The area of the Khulna city corporation is 45.65 km². Salinity poses a significant challenge in coastal regions' groundwater [87, 88], while shallow aquifers are additionally burdened by the presence of high levels of arsenic. The Khulna City Corporation (KCC) is currently experiencing a severe shortage of adequate drinking water. To provide an overview of the current drinking water quality in four residential areas within the Khulna division, the following locations were chosen for analysis: Gollamari (including Islam Nagor, Banargati Road, Khorshed Nagor, Bank town, and Khulna University (KU)), Sonadanga (covering Sonadanga bus terminal, road no 10, 12, 13, Link road, and M A Bari street), Nirala (encompassing road no 4, 13, 21, 23, and 26), and Moilapota (including Ikbali Nagor, Moilapota mor, Sandhya bazaar, Moilapota bypass road, and Basupara road). These areas are depicted in Figure 1.

A total of twenty tube well water samples were collected from various locations, with the sampling points selected in a random manner.

Sample Collection

A total of 20 high density polyethylene (HDPE) bottles with a capacity of 500 mL were purchased from a local market and subsequently utilized for the purpose of sample collection. The sample bottles went through a thorough washing process, consisting of four rinses with deionized water, followed by two rinses with the sample water. Subsequently, the samples were collected. A total of 20 water samples were collected from 20 tube wells within the designated area. Table 1 displays the depth of each sampling tube well and the corresponding duration of its installation.

To maintain a consistent water flow from the tube wells, they were subjected to continuous pumping for a duration of approximately one to two minutes before sampling. The

Table 1. The depth of each sampling tube-well and its installation time

Sampling area	Sample ID	About depth of tube well water (in ft)	Installation duration (in year)
Islam Nagar	S-01	700	12
Banrgati road	S-02	900	8
Bank town	S-03	1100	15
Khorshed Nagar	S-04	980	26
Khulna university	S-05	1300	22
Nirala, road no 4	S-06	1200	7
Nirala, road no 13	S-07	1250	15
Nirala, road no 21	S-08	1400	17
Nirala, road no 23	S-09	1500	13
Nirala, road no 26	S-10	1050	5
Sonadanga bus terminal	S-11	1100	16
Sonadanga, road no 10	S-12	900	40
Sonadanga, road no 12	S-13	850	29
Sonadanga, road no 13	S-14	1000	12
Link road, M A Bari Street	S-15	850	17
Ikbali Nagor	S-16	650	9
Moilapota mor	S-17	700	13
Sandhya bazar	S-18	750	18
Moilapota bypass road	S-19	800	18
Basupara road	S-20	950	12

Source: Owners of each respective tube well.

sample bottles were carefully labeled with distinct sample identifiers, and thorough documentation regarding the sampling locations was diligently recorded for each drinking water source in a dedicated notebook. The provided information encompasses various specifics, such as the identities of the owners, depths of the wells, dates and times of installation, any documented concerns pertaining to the quality of drinking water, and additional relevant details. The HDPE bottles underwent a preliminary cleaning procedure involving rinsing with deionized water three times, followed by triple rinsing with tube well water prior to sample collection [89]. Subsequently, the collected samples were promptly preserved in a cooler with ice to keep them free from external contamination. The samples were expeditiously conveyed to the laboratory for experimental investigation and were preserved under freezing conditions, typically at approximately 4 °C.

Sample Analysis

Various methods were employed to evaluate a variety of physical, chemical, and bacteriological parameters at both sampling locations and in the laboratory, as outlined in Table 2.

Heavy metals such as manganese (Mn), cadmium (Cd), lead (Pb), chromium (Cr), etc. were not tested due to the limitations of the laboratory.

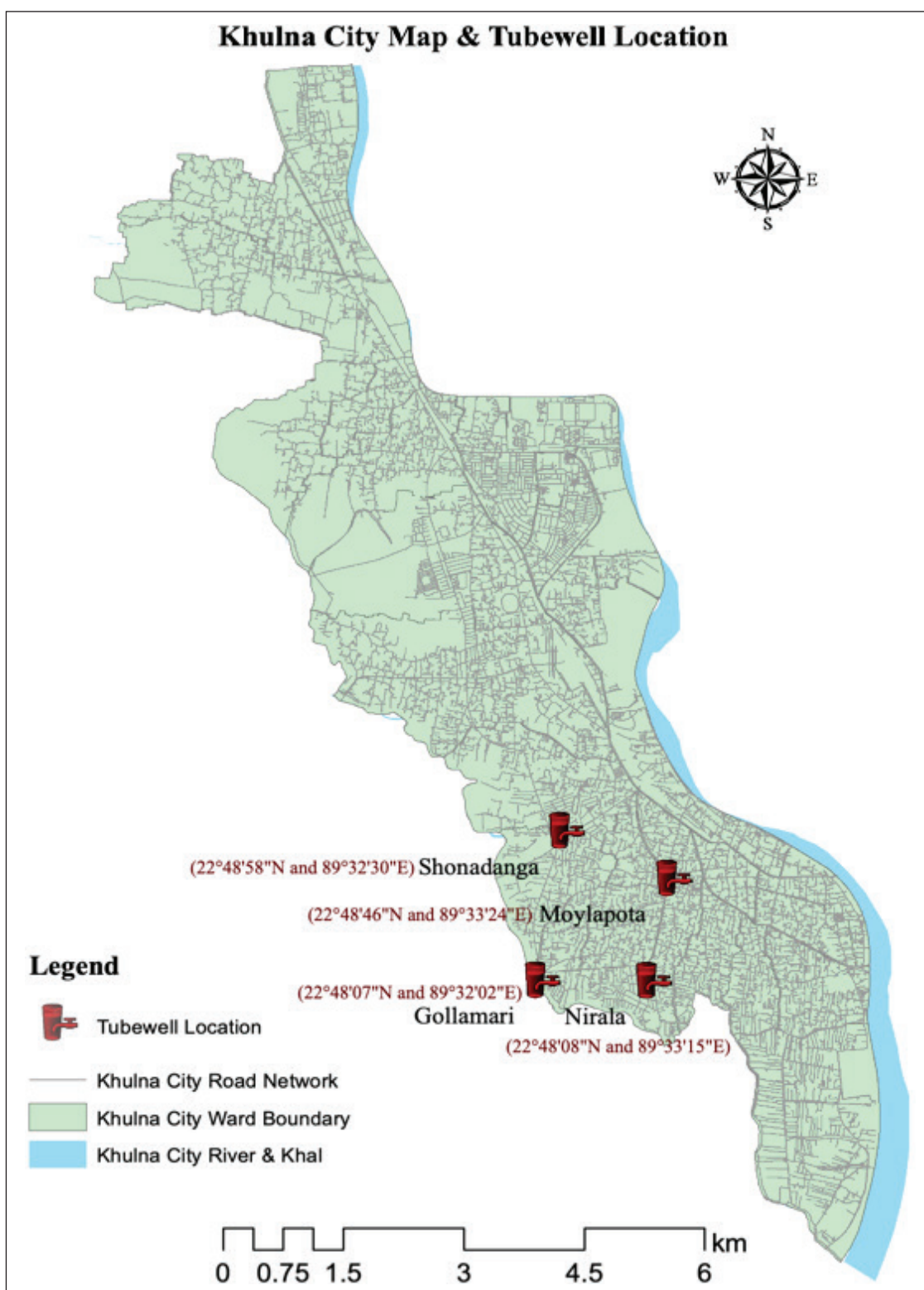


Figure 1. The map of the studied area (17, 23, 24, 25 no. wards were covered out of 31 in Khulna city corporation).

Physical Parameters

Color: The water samples were visually inspected in the laboratory immediately after collection, utilizing direct observation without the aid of any optical instruments.

Odor: The olfactory perception of the water samples is achieved through direct inhalation, allowing the individual to perceive the various odors through the sense of smell.

Taste: The taste of the water samples was assessed through direct consumption.

Total Solid (TS): 50 mL water samples collected from each tube well were transferred into 100 mL beakers and subjected to a 24-hour drying process in an oven at a temperature of 105 °C. The calculation of total solids involved determining the difference between the weights of empty beakers

Table 2. Methods employed for analyzing collected samples and the corresponding units of measurement for the studied parameters

Parameters	Methods		Units
	Temperature	Temperature Probe	°C
Physical	Color	Visualization	–
	Taste	Tongue	–
	Odor	Smelling	–
	Total solids (TS)		mg/L
	Total dissolve solids (TDS)	Filtration, evaporation	mg/L
	Total suspended solids (TSS)	Filtration, evaporation	mg/L
Chemical	Acidity/Alkanity (pH)	Electrometric	–
	Arsenic (As)	Atomic absorption flame spectrometer	mg/L
	Bicarbonates (HCO_3^-)	Titrimetric	mg/L
	Calcium (Ca^{2+})	Titrimetric	mg/L
	Chloride (Cl^-)	Titrimetric	
	Dissolve oxygen (DO)	Electrometric	mg/L
	Electrical conductivity (EC)	Electrometric	$\mu\text{S}/\text{cm}$
	Iron (Fe)	Colorimetric	mg/L
	Magnesium (Mg^{2+})	Titrimetric	mg/L
	Potassium (K^+)	flame emission spectroscopic	mg/L
	Phosphate (PO_4^{3-})	Colorimetric (blue color)	mg/L
	Sodium (Na^+)	Flame emission spectroscopic	mg/L
	Sulfate (SO_4^{2-})	Turbidimetric	mg/L
Bacteriological	Total coliform (TC)	Spread plate	CFU/100 mL
	Fecal coliform (FC)	Spread plate	CFU/100 mL

and the weights of the same beakers containing residual total solids following the removal of water.

Total Dissolved Solids (TDS): A water sample of 50 mL is extracted from each tube well and subsequently subjected to filtration using Whatman 0.45-micron GF/F filter paper. The filtered water is transferred into 100 mL beakers and then undergoes a 24-hour drying process in an oven set at 105 °C. The quantification of TDS is accomplished by calculating the difference in mass between the empty containers and the containers holding the remaining solid substances after the removal of water.

Total Suspended Solids (TSS): After subtracting each sample's TDS value from its TS value, TSS values were recorded.

Chemical Analysis

The samples were subjected to analysis in the laboratories of the Discipline of Soil, Water, and Environment at Khulna University and the Department of Civil Engineering at Khulna University of Engineering and Technology.

pH: The water samples' pH levels are determined by a microprocessor pH meter (Sper Scientific 850051, USA).

Arsenic (As): A Shimadzu AA-7000 atomic absorption flame spectrometer was used to determine the arsenic content of each sample.

Bicarbonate (HCO_3^-): Titrimetric analysis employing a standard 0.086N H_2SO_4 solution is used to determine the concentrations of bicarbonate in the water samples [90].

Calcium (Ca^{2+}): The calcium concentrations in the water samples are determined through the utilization of a titrimetric technique, which involves the application of a standardized 0.01N Ethylenediaminetetraacetic acid (EDTA) solution [91].

Chloride (Cl^-): The concentration of chloride in the water samples is assessed using a titrimetric method involving the utilization of a standardized solution of 0.05N AgNO_3 [92].

Dissolved Oxygen (DO): A digital DO meter (Sper Scientific 850045, USA) was used to assess the levels of dissolved oxygen in the samples.

Electrical Conductivity (EC): A conductivity meter (Sper Scientific 850036, USA) was used to measure the electrical conductivity of the water samples.

Iron (Fe): The iron concentrations in the water samples are analyzed through a colorimetric technique using a spectrophotometer (APEL, PD-303 UV, Japan) set at a wavelength of 510 nm.

Magnesium (Mg^{2+}): Water samples were tested for their total calcium and magnesium content using a titrimetric method with a 0.01N EDTA standard solution [91]. The

Table 3. This table provides a summary of the measured physical parameters of water samples

Sample ID	Color	Odor	Taste	Temperature (°C)	TS (mg/L)	TDS (mg/L)	TSS (mg/L)
S-01	Yellowish	Odorless	Tasteless	27	5600	4000	1600
S-02	Colorless	Odorless	Tasteless	27	2000	1600	400
S-03	Colorless	Odorless	Tasteless	25	1200	800	400
S-04	Yellowish	Odorless	Tasteless	25	6000	4000	2000
S-05	Colorless	Odorless	Tasteless	26	1200	800	400
S-06	Colorless	Odorless	Tasteless	25	1200	800	400
S-07	Colorless	Odorless	Tasteless	27	800	400	400
S-08	Colorless	Odorless	Tasteless	25.4	1600	1200	400
S-09	Colorless	Odorless	Tasteless	25	2800	1600	1200
S-10	Colorless	Odorless	Tasteless	26.1	1200	800	400
S-11	Colorless	Odorless	Tasteless	26	1600	1200	400
S-12	Colorless	Odorless	Tasteless	25	1600	1200	400
S-13	Colorless	Odorless	Tasteless	25.5	2400	1600	800
S-14	Colorless	Odorless	Tasteless	24.8	2000	1200	800
S-15	Colorless	Odorless	Tasteless	25	2400	2000	400
S-16	Yellowish	Odorless	Tasteless	26	1600	1200	400
S-17	Colorless	Odorless	Tasteless	25	1200	800	400
S-18	Colorless	Odorless	Tasteless	25	1200	800	400
S-19	Colorless	Odorless	Tasteless	25	1600	1200	400
S-20	Colorless	Odorless	Tasteless	27	800	400	400

magnesium content was then determined by deducting the calcium content from the combined value.

Phosphate (PO_4^{3-}): The phosphate concentrations in the samples are analyzed using a colorimetric method, specifically the molybdophosphoric blue color technique, conducted with a spectrophotometer (APEL, PD-303 UV, Japan) at a wavelength of 882 nm [93].

Potassium (K^+): A flame photometer (JENWAY, PFP7, UK) was used to determine the potassium concentrations in the water samples.

Sodium (Na^+): A flame photometer (JENWAY, PFP7, UK) was used to determine the sodium concentrations in the collected water samples.

Sulfate (SO_4^{2-}): The turbidimetric method was employed to evaluate the sulfate levels in the water samples [94]. This was done using a spectrophotometer (APEL, PD-303 UV, Japan) configured to a wavelength of 420 nm.

Bacteriological Analysis

Following the guidelines from American Public Health Association (APHA) (2003) [95], the spread plate method was used to find out if the water samples had coliform bacteria or not. Eosin methylene blue agar (EMB) was used as a selective and differentiating medium to find coliform bacteria. It was used to find gram-negative bacteria in particular.

Total Coliform (TC): Labeling each tube with the water sample's source helped count total coliforms. Using a sterilized pipette, each sample's water was spread onto EMB agar plates. Each plate was incubated at 37 °C for 24 hours. In a laminar airflow chamber, the agar plates were placed. Total coliform bacteria in water samples were indicated by red or pink colonies on agar plates.

Fecal coliform (*E. coli* bacteria): After sterilizing a pipette, 1 mL of water from each sample was evenly spread on EMB agar plates to count fecal coliforms. All plates are incubated at 44.5 °C for 24 hours. Agar plates are placed in a laminar airflow chamber after incubation. *E. coli* (fecal coliforms) in water samples is indicated by blue-black colonies with a green metallic sheen on agar plates.

RESULTS AND DISCUSSION

Physical Parameter

Color, odor, taste, temperature, TS, TDS, and TSS are the physical parameters that were used in the experiment. Table 3 displays a summary of the measured physical parameters of the water samples.

TDS and TSS

In the studied area, the values for TS, TDS, and TSS exhibited a range of variability, with TS ranging from 800 to 6000 mg/L, TDS ranging from 400 to 4000 mg/L, and TSS

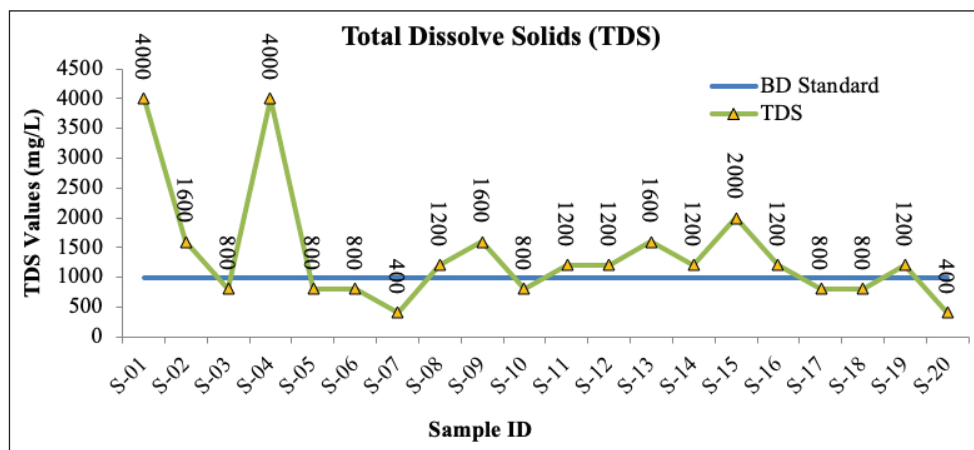


Figure 2. TDS values of the collected water samples.

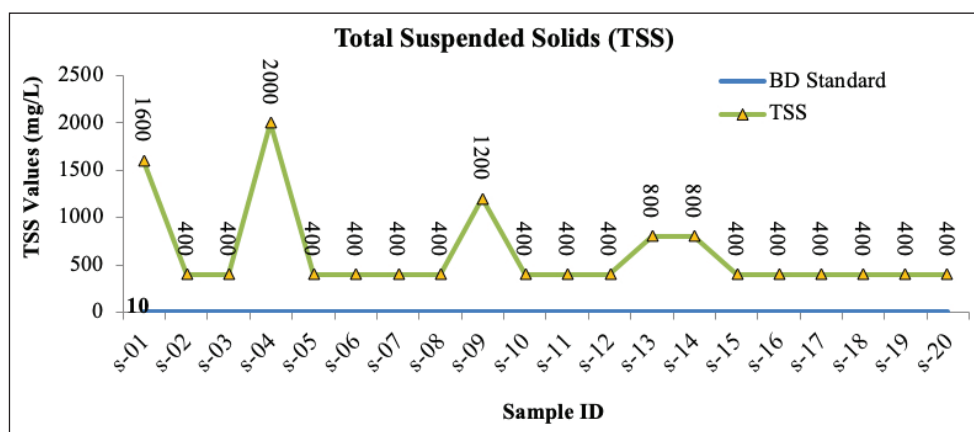


Figure 3. TSS values of the collected water samples.

ranging from 400 to 2000 mg/L. The TDS and TSS measurements of the groundwater in the investigated region are presented in Figures 2 and 3, respectively. These values are compared to the standard set by the ECR in 1997 (Environmental Conservation Rules 1997) known as the BD standard.

The BD regulations mandate TDS and TSS levels of roughly 1000 and 10 mg/L, respectively. According to these criteria, the analysis showed that most of the samples (12 samples) exceeded the recommended TDS values, while the remaining samples (8 samples) were within the acceptable range. Nonetheless, it's noteworthy that every sample was above the TSS limit. It's interesting to note that relatively optimum levels of TSS and TDS may aid in protection against cancer, heart disease, and other chronic illnesses.

Chemical Parameters

The evaluation of groundwater's solute load composition and potential chemical hazards relies heavily on the groundwater's chemical parameters. As, Na^+ , K^+ , Ca^{2+} , Mg^{2+} , Cl^- , HCO_3^- , SO_4^{2-} , and a variety of trace elements are among the common major components of natural water. Table 4 shows the values of the measured chemical parameters of the collected samples.

pH

The pH levels measured in the area were between 7.34 and 8.35. As can be seen in Figure 4, all of the samples had pH levels that fell within the boundaries recommended by both the WHO guidelines and the BD standard.

Arsenic (AS)

The majority of tube wells in the studied area were found to have arsenic levels below the acceptable limits set by both the BD standard (0.05 mg/L) and the WHO guideline (0.01 mg/L), as depicted in Figure 5.

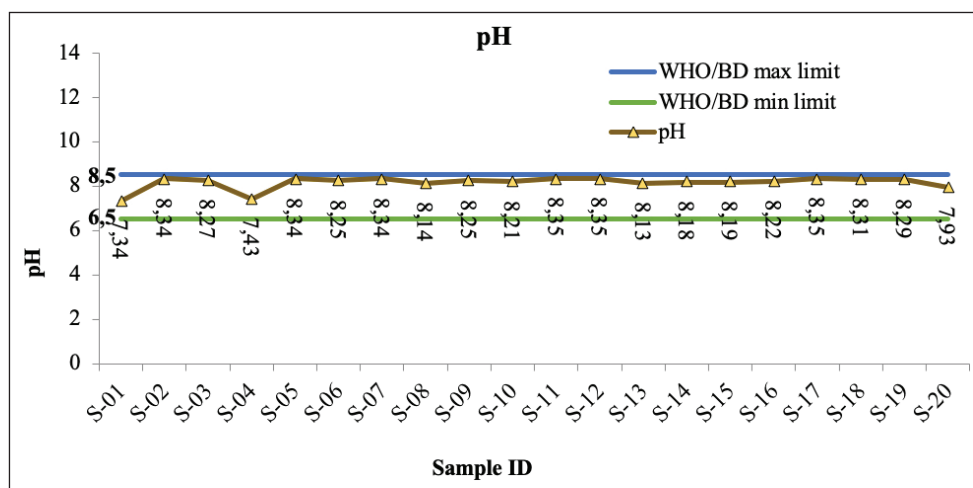
However, two samples, S-01 (0.086 mg/L) and S-04 (0.091 mg/L), exceeded both limits. This indicates a potential arsenic problem in these wells, which could lead to various chronic health issues in humans, including symptoms such as nausea, vomiting, diarrhea, burning of the mouth and throat, and arsenicosis. It is advisable to refrain from the continuous consumption of water from these specific tube wells (S-01 and S-04) to mitigate the risk of these chronic diseases.

Electrical Conductivity (EC)

Figure 6 shows that the conductivity values of the samples from the studied area varied from 300 to 5000 $\mu\text{S}/\text{cm}$. With the exception of samples S-01 and S-04, all of the others were well below the BD standard's upper limit of 700 $\mu\text{S}/\text{cm}$.

Table 4. This table provides a summary of the measured chemical parameters of water samples

Sample ID	pH	As (mg/L)	EC (μS/cm)	DO (mg/L)	HCO ₃ ⁻ (mg/L)	Ca ²⁺ (mg/L)	Cl ⁻ (mg/L)	Fe (mg/L)	Mg ²⁺ (mg/L)	SO ₄ ²⁻ (mg/L)	PO ₄ ³⁻ (mg/L)	K ⁺ (mg/L)	Na ⁺ (mg/L)
S-01	7.34	0.086	5000	6.91	683	36	3195	25	138	5	1.66	212	820
S-02	8.34	0.003	400	4.55	982	30	301	21.25	13	15	2.33	212	350
S-03	8.27	0.004	400	4.22	811	34	88	20	10.8	3	3.5	141	300
S-04	7.43	0.091	4800	6.80	725	118	2946	22.25	108	10	4.5	282	660
S-05	8.34	0.005	300	4.60	939	12	106	17.5	22.8	3.25	2.16	212	450
S-06	8.25	0.005	400	4.62	768	24	124	18.75	15.6	2.5	0.33	141	350
S-07	8.34	0.007	300	4.14	597	30	71	21.25	21.6	10	0.66	212	330
S-08	8.14	0.001	600	5.44	854	34	53	20	24	2.75	4.16	282	290
S-09	8.25	0.008	400	4.47	811	24	106	18.75	32.4	12.5	3.5	141	320
S-10	8.21	0.003	400	4.25	640	28	17.75	18.75	34.8	3.5	11.83	212	510
S-11	8.35	0.001	300	4.80	768	20	88	21.25	8.4	15	0.5	141	490
S-12	8.35	0.002	300	4.55	811	26	124	31.25	10.8	3	2.66	141	550
S-13	8.13	0.006	600	4.29	597	22	301	18.75	18	17.5	10	282	590
S-14	8.18	0.008	500	4.37	683	32	142	20	22.8	2.5	8.16	70.7	630
S-15	8.19	0.007	400	4.75	768	36	159	22.5	19	20	3.83	212	350
S-16	8.22	0.003	400	4.49	725	14	124	16.25	39.6	3	12.16	353	300
S-17	8.35	0.003	300	4.60	896	18	88	21.25	13	17.5	7.16	141	310
S-18	8.31	0.007	300	4.35	1110	12	159	16.25	19	2.75	4.83	212	360
S-19	8.29	0.004	400	4.25	982	22	142	15	12	15	5.83	70.7	400
S-20	7.93	0.004	600	4.29	512	28	124	17.5	18	3.25	5.5	212	420

**Figure 4.** The pH values of the collected water samples.

Considerable evidence suggests that electrical conductivity (EC) is a useful indicator of the concentration of dissolved nutrients in water.

Dissolved Oxygen (DO)

Figure 7 shows that the DO values for the samples collected in the study area varied from 4.22 to 6.91 mg/L. With the exception of samples S-01 and S-04, all other samples (18 samples) were found to be below the BD limit of 6 mg/L.

Having enough DO in the water is essential for keeping it in

good condition. Besides being crucial to aerobic organisms' metabolic processes, DO also contributes a role in influencing inorganic chemical reactions.

Bicarbonates (HCO₃⁻)

The carbonate form was not detected in any of the samples. The HCO₃⁻ content in the samples within the studied area varied between 512 and 1110 mg/L, as illustrated in Figure 8. 85% of the samples (17 samples), apart from other 15% (S-07, S-13, and S-20), exhibited higher bicarbonate levels than the BD standard (600 mg/L).

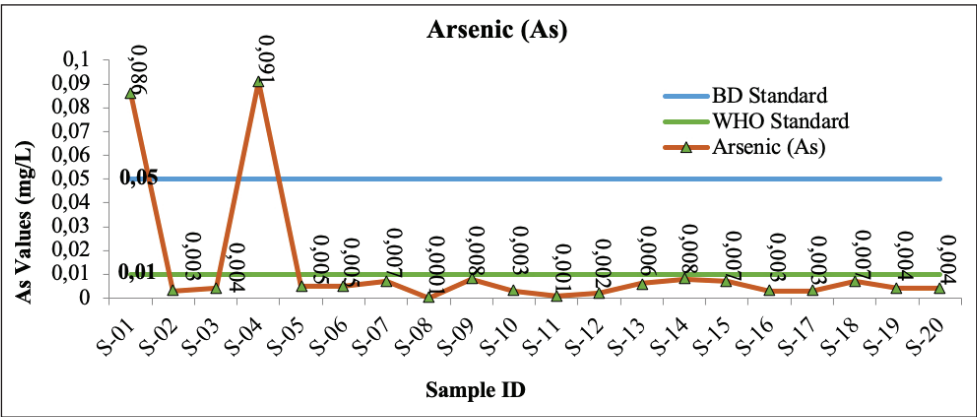


Figure 5. The As values of the collected water samples.

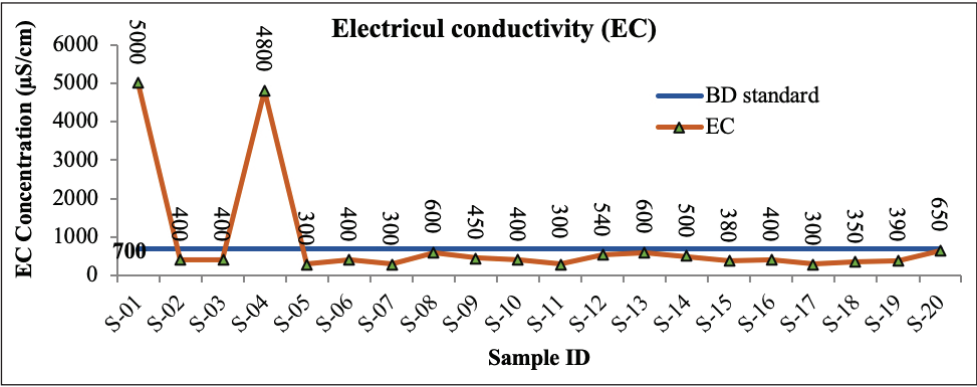


Figure 6. EC values of the collected samples.

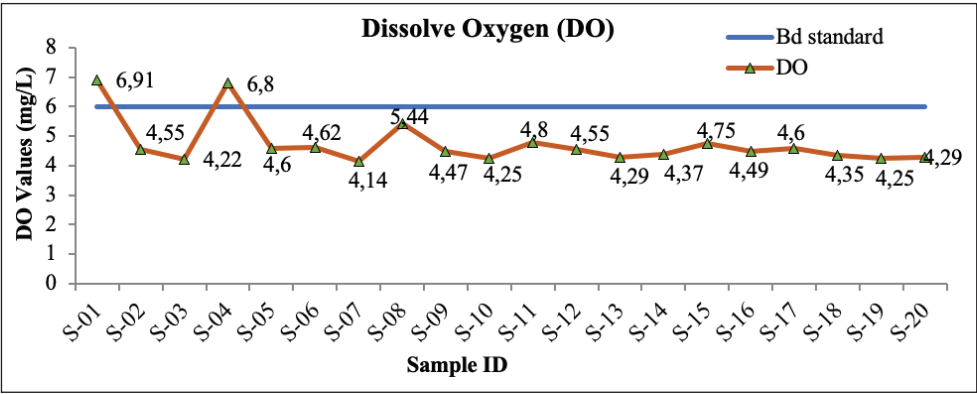


Figure 7. DO values of the collected water samples.

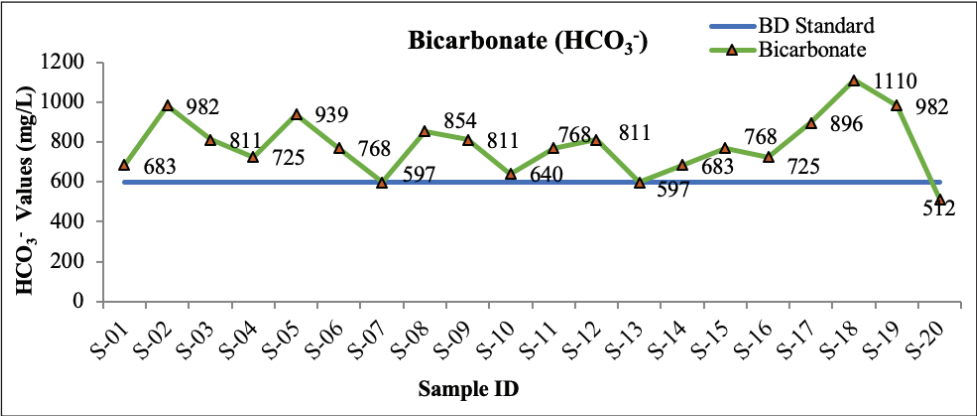


Figure 8. Bicarbonate values of the collected samples.

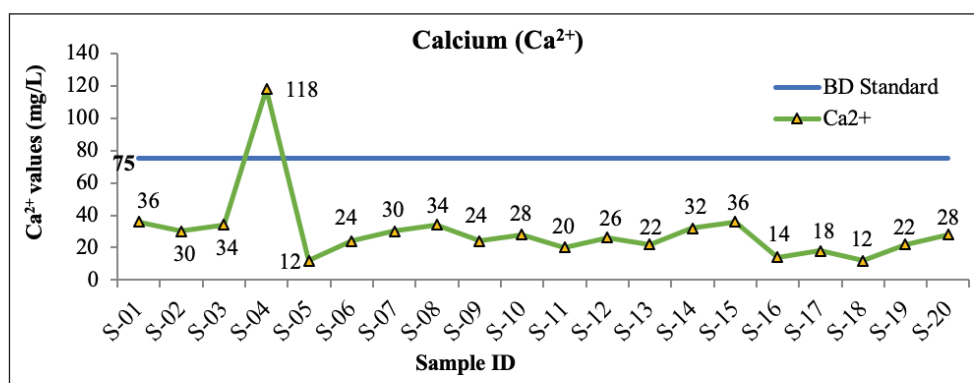


Figure 9. Calcium concentration of the collected water samples.

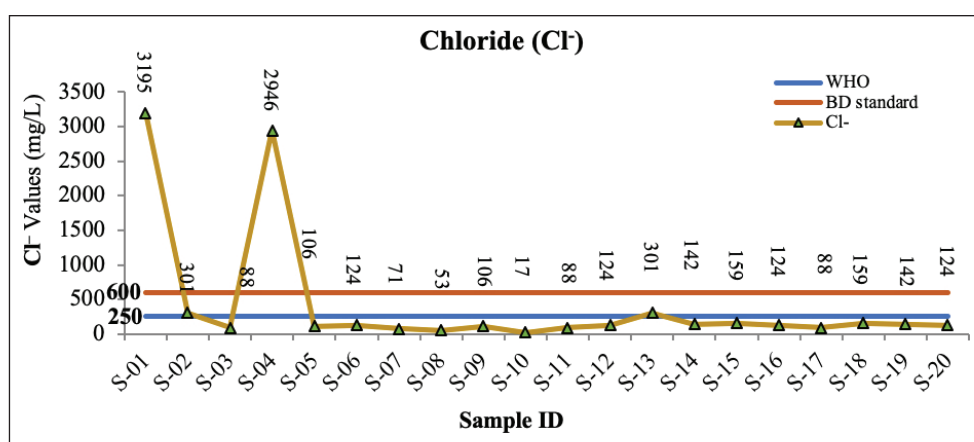


Figure 10. Chloride concentrations of the collected samples.

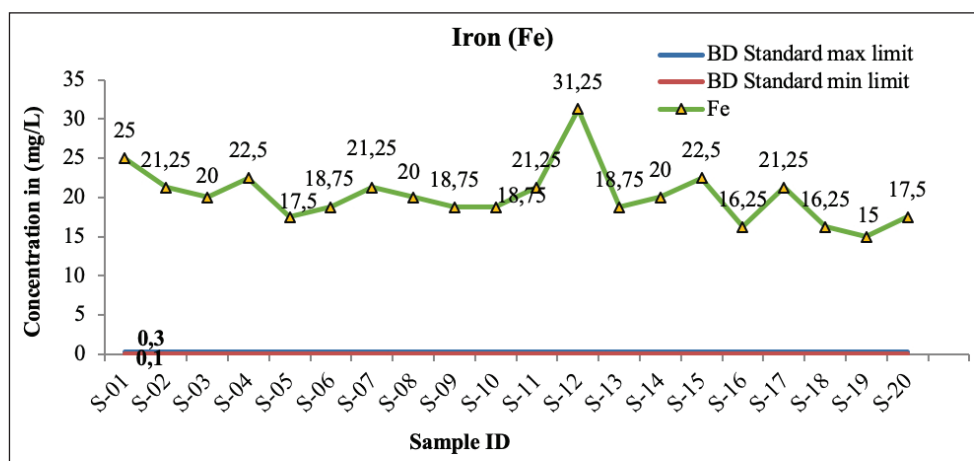


Figure 11. Iron concentrations of the collected water samples.

The acidity of food can be mitigated by consuming an adequate amount of HCO_3^- , which also acts as a buffer for lactic acid produced during exercise. Additionally, it helps keep cavities under control.

Calcium (Ca^{2+})

The calcium content of the samples within the studied area displayed a range of 12–118 mg/L, as depicted in Figure 9. 19 samples out of 20 exhibited calcium concentrations close to the recommended standard of 75 mg/L (BD stan-

dard), with the exception of one sample (S-04) which had a calcium concentration of 118 mg/L. The activity of cell membranes and the body's pH both depend on adequate calcium levels.

Chloride (Cl^-)

Figure 10 shows that the chloride concentrations in the samples collected in the study area ranged widely from 17.75 to 3195 mg/L.

Most samples had chloride concentrations below the min-

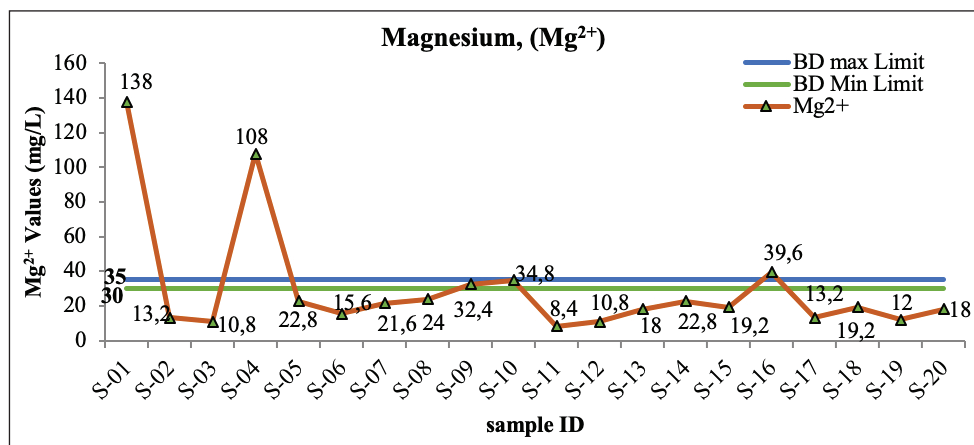


Figure 12. Magnesium concentrations of the collected water samples.

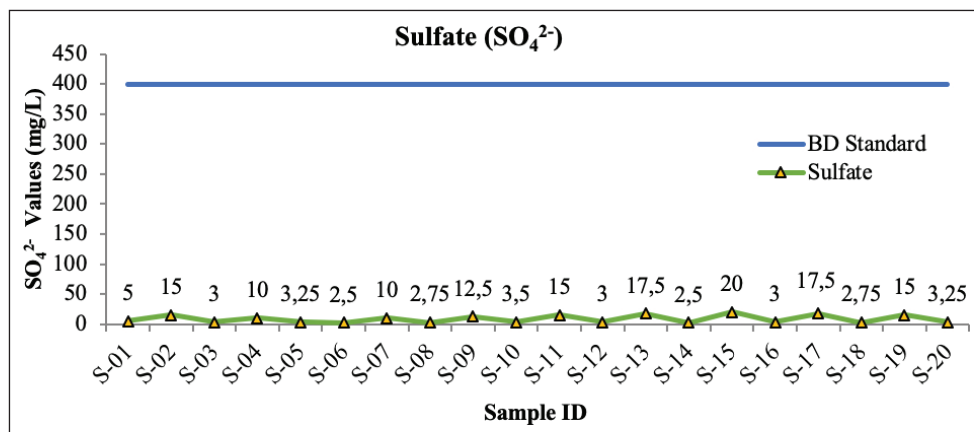


Figure 13. Sulfate concentrations of the collected water samples.

imum and maximum levels allowed (250 mg/L for WHO and 150–600 mg/L for BD, respectively). Two samples, S-01 and S-04, in particular, showed significantly high chloride concentrations. Chloride is essential for the body to keep its fluid levels stable.

Iron (Fe)

The iron concentrations within the samples collected from the study area displayed a range of 15–31.25 mg/L, as illustrated in Figure 11. Notably, all of the samples well exceeded the iron content standard from 0.1 to 0.3 mg/L (BD standard). The iron contents are pretty much concentrated in water samples. Among them S-12 has the highest (31.25 mg/L) and S-19 has the lowest (15 mg/L) concentration.

Symptoms like nausea and vomiting may manifest due to an iron overload, which can lead to serious conditions like diabetes and hemochromatosis, as well as digestive tract problems.

Magnesium (Mg²⁺)

As shown in Figure 12, magnesium concentrations in the samples collected from the study area varied from 8.4 to 138 mg/L. Except for two samples (S-01 and S-04), all of the others were within the tolerance range of 30–35 mg/L (BD standard), which is notable.

Magnesium plays a vital role as an activator of enzymes and is essential for the regulation of neuromuscular excitability and cellular permeability.

Sulfate (SO₄²⁻)

As shown in Figure 13, the sulfate concentrations in the samples taken from the study area varied from 2.5 to 17.5 mg/L. Notably, the SO₄²⁻ levels in all of the samples were significantly lower than the Bangladesh standard of 400 mg/L. Severe chronic diarrhea caused by high sulfate levels is possible, and in extreme cases, it can be fatal.

Phosphate (PO₄³⁻)

Figure 14 depicts the observed range of phosphate concentrations within the samples, which was between 0.33 and 12.16 mg/L.

15 samples out of 20 had concentrations that were below the BD-recommended threshold of 6 mg/L. Elevated levels of PO₄³⁻ were found in four samples (S-10, S-13, S-14, S-16, and S-17), though. DNA materials contain phosphates, and phosphates play an important role in the distribution of energy throughout the body.

Potassium (K⁺)

The potassium content observed in the samples from the

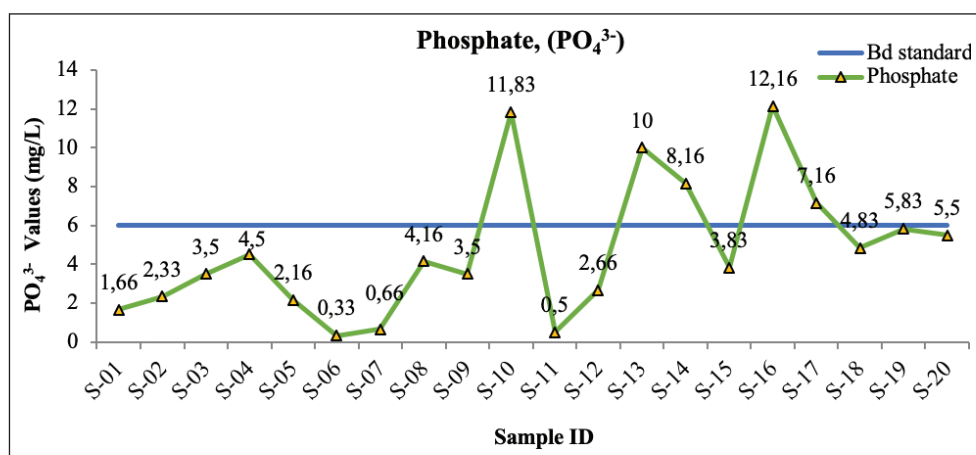


Figure 14. Phosphate concentration of the collected water samples.

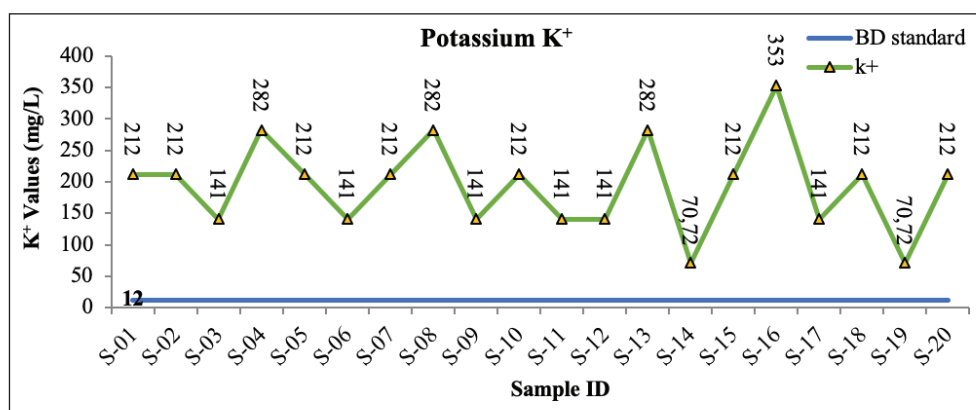


Figure 15. Potassium concentration of the collected water samples.

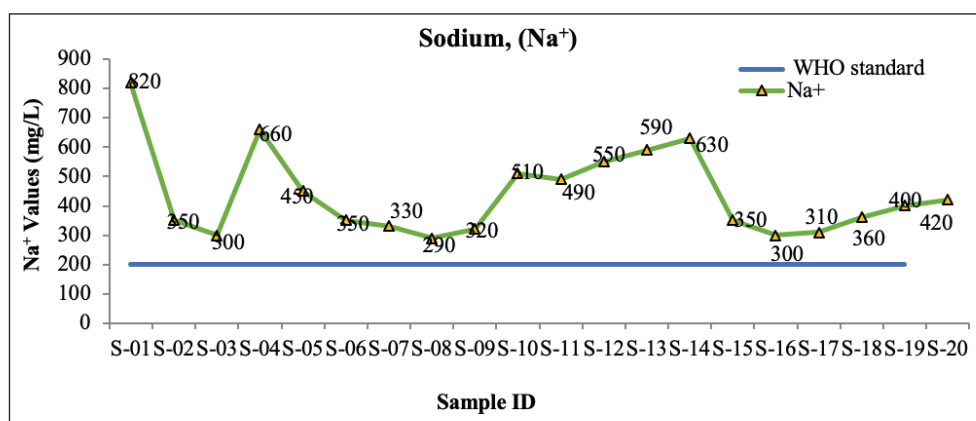


Figure 16. Sodium concentrations of the collected water samples.

study area displayed a range of 70.72 to 353 mg/L, as depicted in Figure 15. Significantly higher levels of K^+ were found in all samples compared to the Bangladesh standard of 12 mg/L. Elevated concentrations of potassium in the body have the potential to induce detrimental health consequences, such as renal dysfunction, cardiac arrhythmias, and hyperkalemia.

Sodium (Na^+)

Sodium concentrations in the studied area's samples ranged from 290 to 820 mg/L, as depicted in Figure 16. All samples

were found to have Na^+ concentrations well above the recommended upper limit of 200 mg/L (WHO and BD standard). A high sodium intake has been linked to an increased risk of developing osteoporosis, stomach cancer, kidney disease, kidney stones, cardiomyopathy, and migraines.

Bacteriological Analysis (TC and FC)

Most samples do not have any detectable levels of coliform bacteria. Figure 17 shows that *E. coli* bacteria are present in only 6 of 20 samples.

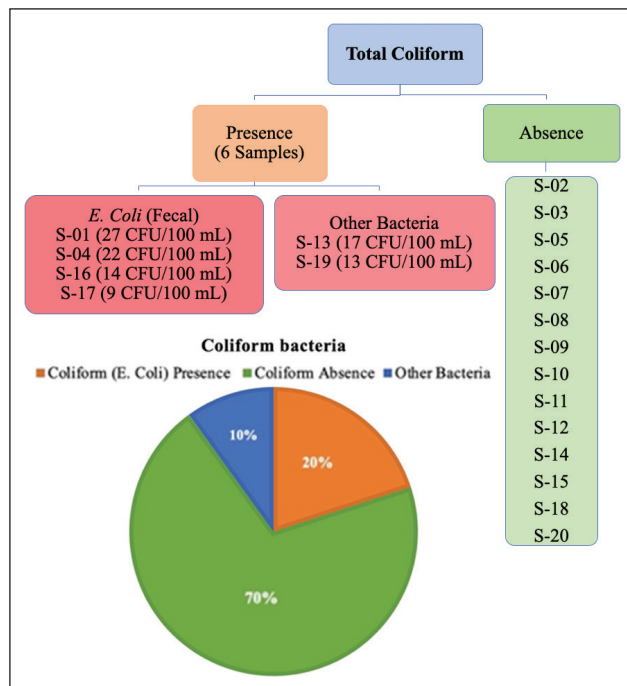


Figure 17. Total coliform and *E. coli* bacterial counts in tested samples.

There is a disproportionately high concentration (visual observation) of *E. coli* in two of the samples (S-01 and S-04). Acute diarrhea, abdominal cramps, nausea, headache, vomiting, and fever are just some of the symptoms of a disease brought on by *E. coli* in the water supply. It's possible that at sufficiently high concentrations, human life might become dead. Possible causes include insufficient tube well depth, a lack of proper sanitation (for example, a short distance between toilets and tube wells), or a lack of quality soil (which would otherwise filter out bacteria in groundwater being pumped from great depths).

DISCUSSIONS

In our study, the average TDS concentration was measured at 1380 mg/L. A comparative study conducted across nine Upazilas in the Khulna region reported a similar TDS concentration of 1089 mg/L, which is slightly lower than the value obtained in this study [96]. It is important to note, though, that the TDS level was much higher in the Khulna district (averaging 1,556.05 mg/L) and in Shyamnagar, Satkhira (averaging 3,691 mg/L), which is higher than the TDS level found in this study [97, 98]. It is important to note that the pH levels in the groundwater samples were between 7.34 and 8.35. This is similar to what another study found, which was a pH of 7.85 ± 0.40 , showing that the pH values are similar [96, 99]. Another study was also found an average pH value of 7.89 ± 0.2 , which backs up the idea that our results are similar to theirs [99]. The average As content in our study was determined to be 0.013 mg/L, which falls below the established standards in BD and closely aligns with the findings of a study that reported an average As concentration of 0.017 mg/L [96, 100]. As levels were also

Table 5. Correlation coefficient between the physical parameters

Parameters	TS	TDS	TSS
TS	1		
TDS	0.988	1	
TSS	0.942	0.878	1

the same in a different study done in the coastal Shyamnagar sub-district of the Satkhira district. It was found to be 0.0166 mg/L, which shows that As levels are consistent in coastal areas [97]. The EC values exhibited a range from 300 to 5000 $\mu\text{S}/\text{cm}$ in this study, with a mean value of 855 $\mu\text{S}/\text{cm}$. Another study that was done in the Khulna district found that EC values varied similarly, ranging from 498 to 5,910 $\mu\text{S}/\text{cm}$, which backs up what we found [98]. In addition, it is worth mentioning that EC values were much higher in the nearby district of Shyamnagar, Satkhira. They were about $7,135.67 \pm 3,433.58$ $\mu\text{S}/\text{cm}$, which is a lot more than the values we found [97].

Apart from samples S-01 and S-04, all samples exhibited DO levels below the established limits in Bangladesh, and this trend is consistent with the findings presented by Mahmud et al. [99] in 2020, where they reported an average DO concentration of 1.61 mg/L in their study of Khulna city. Additionally, another independent study observed a lower average DO value of 3.07 mg/L during the pre-monsoon season in Khulna [101]. These collective findings across different studies underscore the suboptimal status of dissolved oxygen levels in this region, falling significantly below the standard requirements. The chloride (Cl^-) values displayed a wide range, spanning from 17.75 to 3195 mg/L, indicating significant variability. This variation aligns with findings from a 2022 study conducted in the northern part of Khulna city, where the Cl^- content was observed to fluctuate from 21 to 2063 mg/L [102]. Similarly, another study in the Khulna city region reported a comparable range of Cl^- content, ranging from 10 to 3550 mg/L [96]. Notably, a recent investigation in a coastal area of the Satkhira district documented a substantially higher Cl^- content, with an average of $2,940.78 \pm 1,563.5$ mg/L, which is approximately 6.5 times greater than the average value observed in this study [97]. Also, the average chloride level was recorded at $2,005.74 \pm 2,685.5$ mg/L in coastal areas like Khulna, Bagerhat, Satkhira, and Patuakhali [103]. This is a lot higher than the levels seen in this study. This substantial chloride concentration is regarded as an indicative measure of the overall salinity levels, as chloride levels are closely associated with salinity. Hence, the salinity issue in the Khulna district is a matter of concern, as there is ample documentation highlighting the detrimental impact of salinity on human health [104]. The increased salinity levels in the area could be attributed to the dissolution of salts such as NaCl , Na_2CO_3 , KCl , and CaCl_2 from processes such as weathering and rock leaching, the influx of seawater through tidal channels [105], brine shrimp aquaculture activities [106], and the discharge of industrial waste and sewage [107]. Studying high school students in Massachusetts and Chi-

Table 6. Correlation coefficient between the physical parameters

Parameters	pH	As	EC	DO	Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺	Cl ⁻	Fe	SO ₄ ³⁻	PO ₄ ³⁻	HCO ₃ ⁻
pH	1												
As	-0.929	1											
EC	-0.953	0.993	1										
DO	-0.869	0.912	0.933	1									
Ca ²⁺	-0.687	0.747	0.723	0.680	1								
Mg ²⁺	-0.924	0.954	0.961	0.892	0.599	1							
Na ⁺	-0.697	0.698	0.713	0.596	0.403	0.680	1						
K ⁺	-0.329	0.241	0.267	0.311	0.229	0.341	-0.016	1					
Cl ⁻	-0.932	0.992	0.996	0.924	0.699	0.955	0.719	0.254	1				
Fe	-0.217	0.308	0.317	0.386	0.279	0.249	0.413	-0.100	0.335	1			
SO ₄ ³⁻	0.119	-0.034	-0.055	-0.040	0.063	-0.139	-0.094	-0.086	-0.020	0.038	1		
PO ₄ ³⁻	0.019	-0.158	-0.139	-0.247	-0.088	-0.037	0.039	0.309	-0.165	-0.375	-0.042	1	
HCO ₃ ⁻	0.387	-0.187	-0.215	-0.080	-0.225	-0.246	-0.366	-0.226	-0.173	-0.153	0.083	-0.228	1

cago, USA, researchers hypothesized that those living in areas with high salinity (272 mg/L) in their public drinking water would have higher systolic and diastolic blood pressure, with values elevated by 3–5 mmHg compared to those living in areas with low salinity (20 mg/L) [104].

The average iron (Fe) content was determined to be 20.18 mg/L, which is notably higher, approximately three to four times, than a study conducted in the coastal region of Khulna. In the Khulna study, the average Fe content was reported as 6.24±8.41 mg/L during the wet season and 5.13±7.02 mg/L during the dry season [103]. Additionally, a different study done in Shyamnagar and As-sasuni in the Satkhira district found groundwater with Fe levels that were about four times lower, at 4.9±4.76 mg/L and 3.59±2.50 mg/L, respectively [54, 97]. In a recently conducted study within the northern part of Khulna city, which is not in proximity to the sea, notably lower Fe concentrations were observed in their sampled water, ranging from approximately seven to twenty times lower than the Fe levels found in our study [102].

Statistical Analysis

Correlation Between Physical Parameters

Table 5 presents the correlation analysis results between TS, TDS, and TSS. The findings reveal strong correlations among these variables, with TS exhibiting a notably robust positive correlation with TDS ($r=0.988$) and TSS ($r=0.942$). Similarly, TDS and TSS also demonstrate a strong positive correlation ($r=0.878$). These strong correlation coefficients suggest a significant and interrelated association between the variables, indicating their close connection within the dataset.

Correlation Between Chemical Parameters

Table 6 presents the correlation analysis results between pH, As, EC, DO, calcium, magnesium, sodium, potassium, chloride, iron, sulfate, phosphate, and bicarbonate.

pH exhibits a negative correlation with most parameters, except for SO₄³⁻ ($r=0.119$), PO₄³⁻ ($r=0.019$), and HCO₃⁻ ($r=0.387$). Notably, the correlation between pH and HCO₃⁻ is comparatively stronger, signifying a more pronounced association between these two variables within the dataset. Whereas As is positively correlated with all the parameters except the above three parameters. As is very strongly correlated with EC (0.993), DO (0.912), Mg²⁺ (0.954) and Cl⁻ (0.992). Conversely, As demonstrates positive correlations with all parameters, except for SO₄³⁻, PO₄³⁻, and HCO₃⁻. Particularly noteworthy is the remarkably strong positive correlation observed between As and EC ($r=0.993$), DO ($r=0.912$), Mg²⁺ ($r=0.954$), and Cl⁻ ($r=0.992$). EC exhibits a pattern akin to that of As, as it showcases notably strong correlations with DO, Mg²⁺, and Cl⁻. DO is showing negative correlation with SO₄³⁻ ($r=-0.04$), PO₄³⁻ ($r=-0.247$), and HCO₃⁻ ($r=0.080$) among all the parameters. Conversely, the positive correlation observed with other variables suggests that they exhibit synchronized changes, increasing or decreasing in a similar manner in response to variations in the dataset. Ca²⁺ exhibits strong correlations with four parameters, namely As, EC, DO, and Cl⁻. The correlation coefficient values for these associations range from 0.680 to 0.747, indicating a substantial and positive relationship between Ca²⁺ and these parameters. Mg²⁺ also demonstrates positive correlations with 10 chemical parameters out of 13. Notably, it exhibits the most negative correlation with HCO₃⁻, with a coefficient value of -0.246. Conversely, Na⁺ reveals predominantly positive correlations with the parameters. There are only three instances of negative correlation, specifically with K⁺ ($r=0.016$), SO₄³⁻ ($r=-0.094$) and HCO₃⁻ ($r=-0.366$). It is intriguing to note that K⁺ consistently lacks a very strong positive correlation with any parameters. The positive correlation coefficients vary in the range of 0.229 to 0.341. Fe is also demonstrating a pattern like that of K⁺. Among all the positive correlations of Cl⁻ with other parameters, the correlation with Fe ($r=0.335$) is relatively weak. SO₄³⁻, PO₄³⁻, and HCO₃⁻ consistently exhib-

it negative correlations with all parameters except pH, as well as between SO_4^{3-} and HCO_3^- themselves.

Water Quality Status

The comprehensive analysis of the experiment reveals that the examined physical parameters, namely color, odor, and taste, fall within acceptable ranges. However, a significant proportion of the samples exhibited relatively elevated concentrations of TDS and TSS compared to the established standards for drinking water. In terms of chemical parameters, the pH levels were generally within acceptable limits for drinking purposes.

Most of the samples met the prescribed standards for DO (90%), Cl^- (80%), Mg^{2+} (85%), EC (90%), and Ca^{2+} (95%), making them suitable for drinking purposes. SO_4^{2-} levels were notably lower than the acceptable limit. On the contrary, concentrations of Fe, K^+ , Na^+ for all the samples, and, in the case of HCO_3^- , the majority (85%) exceeded the standard ranges for drinking water.

Furthermore, Total Coliform (TC) bacteria were detected in 30% of the samples, with 20% of these instances being *Escherichia coli* (*E. coli* or FC), and the remaining 10% consisting of other types of bacteria. It's important to note that samples meeting acceptable limits for specific parameters may be considered safe for drinking in terms of those particular criteria, while others may not meet the required standards for various parameters, thus impacting their overall suitability for consumption.

CONCLUSION

In summary, the findings of this study provide valuable insights into the quality of tube well water in the investigated regions. While the recorded water temperatures, color, taste, and odor generally met the standard criteria, there were exceptions with some samples exhibiting a slightly yellowish hue. Notably, most samples exhibited elevated TSS values, which significantly exceeded established standards while the TDS values are moderately higher.

The pH levels and parameters such as DO, EC, and Cl^- adhered to recommended conditions for safe drinking, with a few exceptions. Most samples did not contain harmful levels of As, although samples from specific areas showed elevated levels beyond acceptable limits.

Calcium and magnesium ion concentrations were within acceptable ranges for most samples, while iron concentrations exceeded recommended standards across the board. A substantial percentage of samples exhibited acceptable phosphate levels. Bicarbonate concentrations were marginally below standards in only a few samples, with higher levels in the rest. Sodium and potassium ions were present at elevated concentrations in all samples.

While approximately 70% of the samples were free from coliform bacteria, the presence of *E. coli* and other coliform bacteria in 20% and 10% of the samples, respectively, suggests the need for vigilance.

Specific parameters related to color, taste, odor, pH, EC, DO, As, Ca^+ , Cl^- , SO_4^{3-} , and Mg^{2+} were generally suitable for drinking, except for a couple of samples. However, TDS, TSS, Na^+ , K^+ , Fe, HCO_3^- , and PO_4^{3-} levels in all samples were not conducive for drinking.

It is crucial to highlight that coliform bacteria were more prevalent in samples from shallow-depth tube wells, emphasizing the importance of using water from relatively deeper tube wells for drinking to mitigate health risks. The high salinity levels observed in the studied regions render the water unsuitable for drinking, suggesting the potential benefit of utilizing deeper tube wells. Furthermore, the elevated arsenic concentrations in tube wells at Islam Nagar and Khorshed Nagar pose significant health risks, warranting the discontinuation of their use.

While these findings shed light on the water quality in the investigated areas, ongoing monitoring and remediation efforts are essential to ensure safe and accessible drinking water for the local population.

However, it's important to note several limitations in the study:

1. Not all parameters, including trace and toxic elements like Cu, Zn, Pd, Cd, nitrogen species, etc., were analyzed in this study.
2. Limited laboratory facilities may have affected the ability to conduct experiments comprehensively and accurately for certain elements.

ACKNOWLEDGEMENTS

I want to express my sincere and profound gratitude to my respected supervisor, Dr. Khandoker Qudrata Kibria, Professor, Soil, Water and Environment discipline, Khulna University, for his scholastic guidance, valuable suggestions, instructions, and time throughout the progress of this research work and at the preparation of this research. I sincerely thank Professor Dr. Shaikh Motasim Billah, Chair, Soil, Water and Environment Discipline, Khulna University, for providing all possible facilities during this project. Authors also want to thank Civil Engineering Department, Khulna University of Engineering & Technology for their support. There was no funding to support this study.

DATA AVAILABILITY STATEMENT

The author confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

REFERENCES

- [1] K. Roy, Q. Bari, S. Mostakim, and D. B. P. Argha, "Water supply history of Khulna City," 2019.
- [2] P. Roy, M. A. Ahmed, and A. Kumer, "An overview of hygiene practices and health risks related to street foods and drinking water from roadside restaurants of Khulna city of Bangladesh," *EJERE*, Vol. 3(2), pp. 47–55, 2019.
- [3] S.-H. Chong, and S. Ham, "Interaction with the surrounding water plays a key role in determining the aggregation propensity of proteins," *Angewandte Chemie International Edition*, Vol. 53(15), pp. 3961–3964, 2014. [\[CrossRef\]](#)
- [4] R. V. Southwell, S. L. Hilton, J. M. Pearson, L. H. Hand, and G. D. Bending, "Water flow plays a key role in determining chemical biodegradation in water-sediment systems," *Science of The Total Environment*, Vol. 880, Article 163282, 2023. [\[CrossRef\]](#)
- [5] W. J. Cosgrove, and D. P. Loucks, "Water management: Current and future challenges and research directions," *Water Resources Research*, Vol. 51(6), pp. 4823–4839, 2015. [\[CrossRef\]](#)
- [6] M. F. Chaplin, "Water: its importance to life," *Biochemistry and Molecular Biology Education*, Vol. 29(2), pp. 54–59, 2001. [\[CrossRef\]](#)
- [7] Kasim, D. Gursoy, F. Okumus, and A. Wong, "The importance of water management in hotels: a framework for sustainability through innovation," *Journal of Sustainable Tourism*, Vol. 22(7), pp. 1090–1107, 2014. [\[CrossRef\]](#)
- [8] F. Hamzaoui-Azaza, M. Ketata, R. Bouhlila, M. Gueddari, and L. Riberio, "Hydrogeochemical characteristics and assessment of drinking water quality in Zeuss–Koutine aquifer, southeastern Tunisia," *Environmental Monitoring and Assessment*, Vol. 174(1), pp. 283–298, 2011. [\[CrossRef\]](#)
- [9] P. Roy, M. A. Ahmed, Md. S. Islam, Md. A. K. Azad, Md. S. Islam, and Md. R. Islam, "Water supply, sanitation system and water-borne diseases of slum dwellers of Bastuhara Colony, Khulna," presented at the 5th International Conference on Civil Engineering for Sustainable Development (ICCESD 2020), Khulna, Bangladesh: Department of Civil Engg., KUET, 2020.
- [10] S. Varol and A. Davraz, "Evaluation of the groundwater quality with WQI (Water Quality Index) and multivariate analysis: a case study of the Tefenni plain (Burdur/Turkey)," *Environmental Earth Sciences*, Vol. 73(4), pp. 1725–1744, 2015. [\[CrossRef\]](#)
- [11] K. Biswas, "Integrated water resources management: A reassessment," *Water International*, Vol. 29(2), pp. 248–256, 2004. [\[CrossRef\]](#)
- [12] K. Biswas, and C. Tortajada, "Future water governance: Problems and perspectives," *International Journal of Water Resources Development*, Vol. 26(2), pp. 129–139, Jun. 2010. [\[CrossRef\]](#)
- [13] P. H. Gleick, "Water in crisis: Paths to sustainable water use," *Ecological Applications*, Vol. 8(3), pp. 571–579, 1998. [\[CrossRef\]](#)
- [14] H. Tropp, "Water governance: trends and needs for new capacity development," *Water Policy*, Vol. 9(Suppl 2), pp. 19–30, 2007. [\[CrossRef\]](#)
- [15] M. R. Ahmed, M. A. Ahmed, M. Islam, and S. Saha, Study on rainwater harvesting in dacope upazila, Khulna, Bangladesh. 4th International Conference on Advance in Civil Engineering (ICACE 2018), Chittagong, 2018.
- [16] G. Katz, T. B. Coplen, T. D. Bullen, and J. H. Davis, "Use of chemical and isotopic tracers to characterize the interactions between ground water and surface Water in Mantled Karst," *Groundwater*, Vol. 35(6), pp. 1014–1028, 1997. [\[CrossRef\]](#)
- [17] Li, M. L. Wrzesien, M. Durand, J. Adam, and D. P. Lettenmaier, "How much runoff originates as snow in the western United States, and how will that change in the future?," *Geophysical Research Letters*, Vol. 44(12), pp. 6163–6172, 2017. [\[CrossRef\]](#)
- [18] Y. Tsur, "The stabilization role of groundwater when surface water supplies are uncertain: The implications for groundwater development," *Water Resources Research*, Vol. 26(5), pp. 811–818, 1990. [\[CrossRef\]](#)
- [19] R. T. Nickson, J. M. McArthur, B. Shrestha, T. O. Kyaw-Myint, and D. Lowry, "Arsenic and other drinking water quality issues, Muzaffargarh District, Pakistan," *Applied Geochemistry*, Vol. 20(1), pp. 55–68, 2005. [\[CrossRef\]](#)
- [20] N. Carrard, T. Foster, and J. Willetts, "Groundwater as a source of drinking water in Southeast Asia and the Pacific: A multi-country review of current reliance and resource concerns," *Water*, Vol. 11(8), Article 1605, 2019. [\[CrossRef\]](#)
- [21] K. Katsanou, and H. K. Karapanagioti, "Surface water and groundwater sources for drinking water," in *Applications of Advanced Oxidation Processes (AOPs) in Drinking Water Treatment*, A. Gil, L. A. Galeano, and M. Á. Vicente, Eds., in *The Handbook of Environmental Chemistry*. Cham: Springer International Publishing, pp. 1–19, 2019. [\[CrossRef\]](#)
- [22] M. A. Ahmed, M. Hossain, and M. Islam, Prediction of solid waste generation rate and determination of future waste characteristics at South-Western region of Bangladesh using artificial neural network. KUET, Khulna, 2017.
- [23] M. A. Ahmed, and S. D. Chakrabarti, "Scenario of existing solid waste management practices and integrated solid waste management model for developing country with reference to Jhenaidah municipality, Bangladesh," presented at the 4th International Conference on Civil Engineering for Sustainable Development (ICCESD 2018), Khulna, Bangladesh: Department of Civil Engineering, KUET, 2018.
- [24] Md. M. Rahman, D. B. P. Argha, and M. Haque, "Present scenario of municipal solid waste management in Satkhira municipality," *International Con-*

- ference on Civil Engineering for Sustainable Development, Khulna, Bangladesh, 2018.
- [25] T. Khan, D. B. P. Argha, and M. S. Anita, "An Analysis of Existing Medical Waste Management and Possible Health Hazards in Jhenaidah Municipality," 6th International Conference on Engineering Research, Innovation and Education (ICERIE 2021), 26-28 February 2021, pp. 677–683, 2021.
- [26] M. R. Rashid, and M. Ashik, "Evaluation of physico-chemical treatment technologies for landfill leachate induced dissolved organic nitrogen (DON)," AEESP Research and Education Conference, Northeastern University, June 20-23, 2023.
- [27] M. A. Ahmed, and M. Redowan, "Fate and Transport of the Biologically Treated Landfill Leachate Induced Dissolved Organic Nitrogen (DON)," AEESP Research and Education Conference, Northeastern University, June 20-23, 2023, 2023.
- [28] Z. Chengli, M. Ronghua, W. Qi, Y. Mingrui, C. Rui, and Z. Xiaonan, "Photocatalytic degradation of organic pollutants in wastewater by heteropolyacids: a review," *Journal of Coordination Chemistry*, Vol. 74(11), pp. 1751–1764, 2021. [CrossRef]
- [29] M. N. Subramaniam, P. S. Goh, D. Kanakaraju, J. W. Lim, W. J. Lau, and A. F. Ismail, "Photocatalytic membranes: a new perspective for persistent organic pollutants removal," *Environmental Science and Pollution Research*, Vol. 29(9), pp. 12506–12530, 2022. [CrossRef]
- [30] M. Meena, P. Sonigra, G. Yadav, and T. Barupal, "Wastewater treatment techniques: An introduction," in *Removal of Emerging Contaminants Through Microbial Processes*, M. P. Shah, Ed., Singapore: Springer, pp. 161–182, 2021. [CrossRef]
- [31] H. Ghazal, E. Koumaki, J. Hoslett, S. Malamis, E. Katsou, D. Barcelo, and H. Jouhara, "Insights into current physical, chemical and hybrid technologies used for the treatment of wastewater contaminated with pharmaceuticals," *Journal of Cleaner Production*, Vol. 361, Article 132079, 2022. [CrossRef]
- [32] C. K. Chandrawanshi, and K. S. Patel, "Fluoride deposition in central India," *Environmental Monitoring and Assessment*, Vol. 55(2), pp. 251–265, 1999. [CrossRef]
- [33] M. S. Rahaman, "Evaluation of groundwater quality and environmental health in the coastal belt of Khulna, Bangladesh," 2014. https://www.academia.edu/68769922/Evaluation_of_groundwater_quality_and_environmental_health_in_the_coastal_belt_of_Khulna_Bangladesh
- [34] P. K. Chakraborty, "Need of applied research on water quality management," *Indian Journal of Environmental Protection*, Vol. 19(8), pp. 595–597, 1999.
- [35] H. Zhang, G. Xu, H. Zhan, X. Chen, M. Liu, and M. Wang, "Identification of hydrogeochemical processes and transport paths of a multi-aquifer system in closed mining regions," *Journal of Hydrology*, Vol. 589, Article 125344, 2020. [CrossRef]
- [36] Y. Gao, H. Qian, C. Huo, J. Chen, and H. Wang, "Assessing natural background levels in shallow groundwater in a large semiarid drainage Basin," *Journal of Hydrology*, Vol. 584, Article 124638, 2020. [CrossRef]
- [37] Z. Zhang, C. Xiao, O. Adeyeye, W. Yang, and X. Liang, "Source and Mobilization Mechanism of Iron, Manganese and Arsenic in Groundwater of Shuangliao City, Northeast China," *Water*, Vol. 12(2), Article 534, 2020. [CrossRef]
- [38] T. J. Troy, L. C. Bowling, S. A. Jame, C. I. Lee, J. Liu, C. Perry, and B. Richter, "Envisioning a sustainable agricultural water future across spatial scales," *Environmental Research Letters*, Vol. 18(8), Article 085003, 2023. [CrossRef]
- [39] P. Roy, Md. A. Ahmed, and Md. H. Shah, "Biogas generation from kitchen and vegetable waste in replacement of traditional method and its future forecasting by using ARIMA model," *Waste Disposal & Sustainable Energy*, Vol. 3(2), pp. 165–175, 2021. [CrossRef]
- [40] Md. A. Ahmed, P. Roy, A. Bari, and M. Azad, *Conversion of Cow Dung to Biogas as Renewable Energy Through Mesophilic Anaerobic Digestion by Using Silica Gel as Catalyst*, 5th ed. Chittagong: IC-MERE 2019, Chittagong University of Engineering & Technology (CUET), 2019.
- [41] A. Kumar, A. Ranjan, K. Gulati, S. Thakur, and T. Jindal, "Assessment of chemical and microbial contamination in groundwater through leaching of sewage waste in Delhi, India," *Environmental Earth Sciences*, Vol. 75(3), Article 275, 2016. [CrossRef]
- [42] R. R. Dash, I. Mehrotra, P. Kumar, and T. Grischek, "Lake bank filtration at Nainital, India: water-quality evaluation," *Hydrogeology Journal*, Vol. 16(6), pp. 1089–1099, 2008. [CrossRef]
- [43] M. Mahmud, S. Mukharjee, M. Khalil, M. Rahman, and F. Hossen, "Physicochemical and Microbiological analysis of tube-well water from Noakhali district, Bangladesh," *World Journal of Microbiology*, Vol. 3, pp. 43–49, 2016.
- [44] R. Datta, M. Hossain, M. Aktaruzzaman, and A. N. M. Fakhruddin, "Antimicrobial resistance of pathogenic bacteria isolated from tube well water of costal area of Sitakunda, Chittagong, Bangladesh," *Effluent and Water Treatment Journal*, Vol. 1, pp. 1–6, 2013. [CrossRef]
- [45] M. Shaibur, M. Hossain, and S. Sony, "Drinking water quality of hand tube well water at sub-urban areas of Jashore Municipality, Bangladesh," Vol. 4, pp. 11–22, 2019.
- [46] M. S. Islam, A. Siddika, M. N. H. Khan, M. M. Golder, M. A. Sadique, A. N. M. H. Kabir, A. Huq, and R. R. Colwell, "Microbiological analysis of tube-well water in a rural area of Bangladesh," *Applied and Environmental Microbiology*, Vol. 67(7), pp. 3328–3330, 2001. [CrossRef]
- [47] D. van Halem, S. Olivero, W. W. J. M. de Vet, J. Q. J.

- C. Verberk, G. L. Amy, and J. C. van Dijk, "Subsurface iron and arsenic removal for shallow tube well drinking water supply in rural Bangladesh," *Water Research*, Vol. 44(19), pp. 5761–5769, 2010. [CrossRef]
- [48] M. G. M. Alam, G. Allinson, F. Stagnitti, A. Tanaka, and M. Westbrooke, "Arsenic contamination in Bangladesh groundwater: A major environmental and social disaster," *International Journal of Environmental Health Research*, Vol. 12(3), pp. 235–253, 2002. [CrossRef]
- [49] S. Luby, M. S. Islam, and R. Johnston, "Chlorine spot treatment of flooded tube wells, an efficacy trial," *Journal of Applied Microbiology*, Vol. 100(5), pp. 1154–1158, 2006. [CrossRef]
- [50] T. Prosun, M. Rahaman, S. Rikta, and M. Rahman, "Drinking water quality assessment from ground water sources in Noakhali, Bangladesh," *International Journal of Development and Sustainability*, Vol 7(5), pp. 1676–1687, 2018.
- [51] M. R. Shaibur, M. S. Hossain, S. Khatun, and F. K. S. Tanzia, "Assessment of drinking water contamination in food stalls of Jashore Municipality, Bangladesh," *Applied Water Science*, Vol. 11(8), Article 142, 2021. [CrossRef]
- [52] A. J. Pickering, A. Ercumen, B. F. Arnold, L. H. Kwong, S. M. Parvez, M. Alam, D. Sen, S. Islam, C. Kullmann, C. Chase, R. Ahmed, L. Unicomb, J. M. Colford Jr, and S. P. Luby, "Fecal Indicator Bacteria along Multiple Environmental Transmission Pathways (Water, Hands, Food, Soil, Flies) and Subsequent Child Diarrhea in Rural Bangladesh," *Environmental Science & Technology*, Vol. 52(14), pp. 7928–7936, Jul. 2018. [CrossRef]
- [53] S. Sarker et al., "Quality Assessment of Surface and Drinking Water of Nakla Paurosova, Sherpur, Bangladesh," *Advances in Microbiology*, Vol. 09(08), Article 08, 2019. [CrossRef]
- [54] Md. A. Rahman, S. Kumar, A. A. Mohana, R. Islam, Md. A. Hashem, and L. Chuanxiu, "Coliform bacteria and trace metals in drinking water, Southwest Bangladesh: Multivariate and human health risk assessment," *International Journal of Environmental Research*, Vol. 13(2), pp. 395–408, 2019. [CrossRef]
- [55] T. Islam, M. Acharjee, N. Tabassum, and M. R. Acharjee, "Bacterial propagation in municipal water and deep tube-well water in Kashipur Locality of Narayanganj City, Bangladesh," *Journal of Water and Environment Technology*, Vol. 18(5), pp. 327–337, 2020. [CrossRef]
- [56] D. D. Mara, and R. G. A. Feachem, "Water- and excreta-related diseases: Unitary environmental classification," *Journal of Environmental Engineering*, Vol. 125(4), pp. 334–339, 1999. [CrossRef]
- [57] K. Yang, J. LeJeune, D. Alsdorf, B. Lu, C. K. Shum, and S. Liang, "Global distribution of outbreaks of water-associated infectious diseases," *PLOS Neglected Tropical Diseases*, Vol. 6(2), Article e1483, 2012. [CrossRef]
- [58] P. K. Pandey, P. H. Kass, M. L. Soupir, S. Biswas, and V. P. Singh, "Contamination of water resources by pathogenic bacteria," *AMB Express*, Vol. 4(1), Article 51, 2014. [CrossRef]
- [59] G. Cissé, "Food-borne and water-borne diseases under climate change in low- and middle-income countries: Further efforts needed for reducing environmental health exposure risks," *Acta Tropica*, Vol. 194, pp. 181–188, 2019. [CrossRef]
- [60] J. A. Adetunji, "Response of parents to five killer diseases among children in a Yoruba community, Nigeria," *Social Science & Medicine*, Vol. 32(12), pp. 1379–1387, 1991. [CrossRef]
- [61] H. Irena, M. Mwambazi, and V. Mulenga, "Diarrhea is a major killer of children with severe acute malnutrition admitted to inpatient set-up in Lusaka, Zambia," *Nutrition Journal*, Vol. 10(1), Article 110, 2011. [CrossRef]
- [62] N. Simakachorn, V. Pichaipat, P. Rithipornpaisarn, C. Kongkaew, P. Tongpradit, and W. Varavithya, "Clinical evaluation of the addition of lyophilized, heat-killed lactobacillus acidophilus LB to oral rehydration therapy in the treatment of acute diarrhea in children," *Journal of Pediatric Gastroenterology and Nutrition*, Vol. 30(1), Article 68, 2000. [CrossRef]
- [63] W. P. Cunningham, M. A. Cunningham, and B. W. Saigo, "Environmental science: A global concern, Vol. 412," McGraw-Hill; 2001.
- [64] E. Lopez-Gunn and W. T. Jarvis, "Groundwater governance and the Law of the Hidden Sea," *Water Policy*, vol. 11(6), pp. 742–762, 2009. [CrossRef]
- [65] W. T. Jarvis, "Transboundary groundwater: geopolitical consequences, commons sense, and the law of the hidden sea." [Doctorial Thesis], Oregon State University.
- [66] W. T. Jarvis, "Integrating Groundwater Boundary Matters into Catchment Management," in *The Dilemma of Boundaries: Toward a New Concept of Catchment*, M. Taniguchi and T. Shiraiwa, Eds., Global Environmental Studies., Tokyo: Springer Japan, 2012, pp. 161–176. [CrossRef]
- [67] Massoud MA, Al-Abady A, Jurdi M, and Nuwayhid I, "The challenges of sustainable access to safe drinking water in rural areas of developing countries: case of Zawtar El-Charkieh, Southern Lebanon," *Journal of Environmental Health*, Vol. 72(10), pp. 24–30, 2010.
- [68] B. J. Lloyd, and J. K. Bartram, "Surveillance solutions to microbiological problems in water quality control in developing countries," *Water Science and Technology*, Vol. 24(2), pp. 61–75, 1991. [CrossRef]
- [69] M. D. Sobsey, "Drinking water and health research: a look to the future in the United States and globally," *Journal of Water and Health*, Vol. 4(Suppl 1), pp. 17–21, 2006. [CrossRef]
- [70] World Health Organization, "Guidelines for Drinking-water Quality," World Health Organization, 2004.

- [71] F. X. R. van Leeuwen, "Safe drinking water: the toxicologist's approach," *Food and Chemical Toxicology*, Vol. 38, pp. S51–S58, 2000. [CrossRef]
- [72] M. H. Minar, M. B. Hossain, and M. Samsuddin, "Climate change and coastal zone of Bangladesh: Vulnerability, resilience and adaptability," *Middle-East Journal of Scientific Research*, Vol. 13, pp. 114–120, 2013.
- [73] M. A. Baten, L. Seal, and K. S. Lisa, "Salinity intrusion in interior coast of Bangladesh: Challenges to agriculture in South-Central Coastal Zone," *American Journal of Climate Change*, Vol. 4(3), 2015. [CrossRef]
- [74] R. Chakraborty, K. M. Khan, D. T. Dibaba, M. A. Khan, A. Ahmed, and M. Z. Islam, "Health implications of drinking water salinity in coastal areas of Bangladesh," *International Journal of Environmental Research and Public Health*, Vol. 16(19), Article 3746, 2019. [CrossRef]
- [75] U. Habiba, Md. A. Abedin, R. Shaw, and A. W. R. Hassan, "Salinity-induced livelihood stress in coastal region of Bangladesh," in *Water Insecurity: A Social Dilemma*, Emerald Group Publishing Limited, pp. 139–165, 2014. [CrossRef]
- [76] S. Rasheed, S. Jahan, T. Sharmin, S. Hoque, M. A. Khanam, M. A. Land, M. Iqbal, S. M. A. Hanifi, F. Khatun, A. K. Siddique, and A. Bhuiya, "How much salt do adults consume in climate vulnerable coastal Bangladesh?," *BMC Public Health*, Vol. 14(1), Article 584, 2014. [CrossRef]
- [77] C. Li, X. Gao, S. Li, and J. Bundschuh, "A review of the distribution, sources, genesis, and environmental concerns of salinity in groundwater," *Environmental Science and Pollution Research*, Vol. 27(33), pp. 41157–41174, 2020. [CrossRef]
- [78] Md. M. Rahman and M. M. Rahaman, "Impacts of Farakka barrage on hydrological flow of Ganges river and environment in Bangladesh," *Sustainable Water Resources Management*, Vol. 4(4), pp. 767–780, 2018. [CrossRef]
- [79] N. Saito, "Bangladesh: Strengthening the Resilience of the Water Sector in Khulna to Climate Change," 2008. <https://policycommons.net/artifacts/401066/bangladesh/1370051/>
- [80] M. A. Kawser, and M. A. Samad, "Political history of Farakka Barrage and its effects on environment in Bangladesh," *Bandung*, Vol. 3(1), pp. 1–14, 2016. [CrossRef]
- [81] Md. S. Hossain, J. A. Dearing, M. M. Rahman, and M. Salehin, "Recent changes in ecosystem services and human well-being in the Bangladesh coastal zone," *Regional Environmental Change*, Vol. 16(2), pp. 429–443, 2016. [CrossRef]
- [82] M. H. Rahman, T. Lund, and I. Bryceson, "Salinity impacts on agro-biodiversity in three coastal, rural villages of Bangladesh," *Ocean & Coastal Management*, Vol. 54(6), pp. 455–468, 2011. [CrossRef]
- [83] K. Roy, A. K. Gain, B. Mallick, and J. Vogt, "Social, hydro-ecological and climatic change in the southwest coastal region of Bangladesh," *Regional Environmental Change*, Vol. 17(7), pp. 1895–1906, 2017. [CrossRef]
- [84] M. B. Alam, C. R. Kabir Rocky, N. S. Tarakki, A. Al Aftab, and C. Quamruzzaman, "Groundwater and surface water quality assessment for irrigation and drinking purposes of Khulna District, South-Western, Bangladesh," *International Journal of Scientific and Engineering Research*, Vol. 6(2), Article 470, 2015.
- [85] M. A. Abedin, and R. Shaw, "Safe water adaptability for salinity, arsenic and drought risks in Southwest of Bangladesh," *Risk, Hazards & Crisis in Public Policy*, Vol. 4(2), pp. 62–82, 2013. [CrossRef]
- [86] M. A. Abedin, U. Habiba, and R. Shaw, "Community perception and adaptation to safe drinking water scarcity: salinity, arsenic, and drought risks in coastal Bangladesh," *International Journal of Disaster Risk Science*, Vol. 5(2), pp. 110–124, 2014. [CrossRef]
- [87] T. Roy, D. Chandra, M. M. A. A. M. Sony, and M. S. Rahman, "Impact of salinity intrusion on health of coastal people: reflections from dacope upazila of Khulna District, Bangladesh," *Khulna University Studies*, pp. 57–66, 2020. [CrossRef]
- [88] M. Akib Javed, A. Paul, and T. K. Nath, "Peoples' perception of the water salinity impacts on human health: a case study in South-Eastern Coastal Region of Bangladesh," *Expo Health*, Vol. 12(1), pp. 41–50, 2020. [CrossRef]
- [89] J. Aryal, B. Gautam, and N. Sapkota, "Drinking water quality assessment," *Journal of Nepal Health Research Council*, 2012.
- [90] M. L. Jackson, *Soil Chemical Analysis*. Prentice Hall Inc., 1958. <http://archive.org/details/soilchemicalanal030843mbp>
- [91] G. Schwarzenbach, W. Biedermann, and F. Bangertner, "Complexones VI. New simple titration methods for determining water hardness," *Helvetica Chimica Acta*, Vol. 29(4), pp. 811–818, 1946. [CrossRef]
- [92] M. L. Jackson, "Soil chemical analysis," *Prentice Hall of India Pvt. Ltd.*, 1973.
- [93] M. Jackson, "Soil chemical analysis prentice," *Hall of India Private Limited*, Vol. 498(1), 1967.
- [94] J. Hunt, "Determination of total sulphur in small amounts of plant material," *Analyst*, Vol. 105(1246), pp. 83–85, 1980. [CrossRef]
- [95] L. S. Clesceri, "Standard methods for examination of water and wastewater," *American Public Health Association*, Vol. 9, 1998.
- [96] Md. A. Rahman, Md. R. Islam, S. Kumar, and S. M. Al-Reza, "Drinking water quality, exposure and health risk assessment for the school-going children at school time in the southwest coastal of Bangladesh," *Journal of Water, Sanitation and Hygiene for Development*, Vol. 11(4), pp. 612–628, 2021. [CrossRef]
- [97] M. A. Rakib, J. Sasaki, H. Matsuda, S. B. Quraishi, M. J. Mahmud, M. Bodrud-Doza, A. K. M. Atique Ullah,

- K. J. F, M. A. Newaz, and M. A.H. Bhuiyan, "Ground-water salinization and associated co-contamination risk increase severe drinking water vulnerabilities in the southwestern coast of Bangladesh," *Chemosphere*, Vol. 246, Article 125646, 2020. [\[CrossRef\]](#)
- [98] S. D.-U. Islam, M. A. H. Bhuiyan, T. Rume, and G. Azam, "Hydrogeochemical investigation of groundwater in shallow coastal aquifer of Khulna District, Bangladesh," *Applied Water Science*, Vol. 7, pp. 4219–4236, 2017. [\[CrossRef\]](#)
- [99] Mahmud, S. Sikder, and J. C. Joardar, "Assessment of groundwater quality in Khulna city of Bangladesh in terms of water quality index for drinking purpose," *Applied Water Science*, Vol. 10(11), Article 226, 2020. [\[CrossRef\]](#)
- [100] M. A. Rahman, and M. A. Hashem, "Arsenic, iron and chloride in drinking water at primary school, Satkhira, Bangladesh," *Physics and Chemistry of the Earth, Parts A/B/C*, Vol. 109, pp. 49–58, 2019. [\[CrossRef\]](#)
- [101] M. Sikder, N. Mistri, M. Rahaman, and N. Saiara, "Evaluation of groundwater quality and environmental health in the coastal belt of Khulna, Bangladesh," *Journal of Biological Pharmaceutical and Chemical Research*, Vol. 1, pp. 113–122, 2014.
- [102] Q. H. Bari, M. Shafiquzzaman, and Q. S. Bari, "Success rate in sinking deep tube-wells to search new water source in the northern periphery of Khulna city," in 6th International conference on civil engineering for sustainable development (ICCESD), pp. 10–12, 2022.
- [103] R. M. T. Islam, M. T. Siddiqua, A. Zahid, S. S. Tassim, and M. M. Rahman, "Drinking appraisal of coastal groundwater in Bangladesh: An approach of multi-hazards towards water security and health safety," *Chemosphere*, Vol. 255, Article 126933, 2020. [\[CrossRef\]](#)
- [104] P. Vineis, Q. Chan, and A. Khan, "Climate change impacts on water salinity and health," *Journal of Epidemiology and Global Health*, Vol. 1(1), pp. 5–10, 2011. [\[CrossRef\]](#)
- [105] M. Rahman, M. Sohel, and F. Ahmed, "Physico-chemical and bacteriological analysis of drinking tube-well water from some primary school, Magura, Bangladesh to evaluate suitability for students," *International Journal of Applied Sciences and Engineering Research*, Vol. 4(10), pp. 355–360, 2015.
- [106] J. C. Ayers, G. George, D. Fry, L. Benneyworth, C. Wilson, L. Auerbach, K. Roy, R. Karim, F. Akter, and S. Goodbred, "Salinization and arsenic contamination of surface water in southwest Bangladesh," *Geochemical Transactions*, Vol. 18, pp. 1–23, 2017. [\[CrossRef\]](#)
- [107] Y. Meride, and B. Ayenew, "Drinking water quality assessment and its effects on residents health in Wondo genet campus, Ethiopia," *Environmental Systems Research*, Vol. 5(1), pp. 1–7, 2016. [\[CrossRef\]](#)



Research Article

The relationship between air pollution and cardiovascular diseases in Türkiye

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ARTICLE INFO

Article history

Received: 20 June 2023

Revised: 03 November 2023

Accepted: 27 November 2023

Key words:

Air pollution; Cardiovascular diseases, Econometric analysis; Machine learning

ABSTRACT

The aim of this study was to determine the effect of air pollutant particles on the cardiovascular disease burden (CVDALY) in Türkiye. Particulate Matter 2.5 (PM 2.5) and Non-methane volatile organic compounds (NMVOC) were taken as the independent variable and CVDALY as the dependent variable. The variables were analyzed within the Panel Data Analysis and Machine Learning Approaches frame. Unidirectional Granger causality was determined from PM 2.5-NMVOC to CVDALY and revealed that they acted together in the long term. The regression analysis that was made using econometric and multivariate regression models revealed that generally 1 unit increase in PM 2.5 increased CVDALY by between 0.0021–0.0029 units; 1 unit increase in NMVOC increased CVDALY by between 0.00024–0.0004 units. In Machine Learning approach, it had been determined that if the PM 2.5 and NMVOC were reduced to 0.84- and 9.48 respectively; CVDALY would be decreased to 0.022. In other words, Machine Learning approaches results showed that reducing PM 2.5 by about 4.5 times and NMVOC by about 30% would be reduced CVDALY by about 39.6% from the current status of Türkiye. The empirical results showed that PM 2.5 - NMVOC increased CVDALY in Türkiye. From this perspective establishing and implementing policies to improve air quality in Türkiye could be an important approach in reducing cardiovascular diseases.

Cite this article as: Ekinici G. The relationship between air pollution and cardiovascular diseases in Türkiye. Environ Res Tec 2024;7(1)61–70.

INTRODUCTION

The development of industry, increasing population, prolonged life expectancy, and urbanization have brought air pollution to the fore, so air pollution has become one of the major problems threatening human health today. Air pollution occurs when the foreign substances in the air reach a certain density above the amount they should be. Sources of air pollution are based on natural and artificial (anthropogenic) causes. While natural causes are volcanic eruptions, forest fires, dust, and pollen; traffic, home heating, cooking, construction, industry, mechanical wear, power plants, agriculture, etc. are the artificial causes. The

most important air pollutants particles are Azotoxides (NO_x), Carbon monoxide (CO), Carbon Dioxide (CO₂), Hydrocarbons (HC), Ozone (O₃), Particulate Matter (PM), and Sulfur dioxide (SO₂). Many environmental factors affect our health. Even taking very low concentrations of these factors into the body by absorption/inhalation etc. adversely affects the life of living things and these environmental polluters can be increased the risk of diseases such as asthma, cancer, and heart disease [1]. Air polluters effect on the cardiovascular, respiratory and neurological systems. For example, PM exposure on the cardiovascular diseases are different like oxidative stress injuries, systemic inflammation, cardiac autonomic function or endothelial

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A part of this study was presented as a summary paper at the 4th International 22nd National Public Health Congress.



dysfunction [2]. It has been frequently studied in the literature that pollutants cause an increase in blood pressure, changes in heart rhythm such as arrhythmia, myocardial infarction due to thickening of the vessel wall, atherosclerosis, cardiac hypertrophy, increase in plasma viscosity, and thrombus formation [3–8]. Air pollutants increase epithelial permeability by damaging epithelial cells in the respiratory tract and cause a range of inflammatory effects such as cell inflammation and cytokine increase [3]. Air pollution causes a decrease in respiratory functions, exacerbation of asthma and chronic obstructive pulmonary disease (COPD), and developmental delay of the lungs. Depending on these, it may cause an increase in the cardiopulmonary death rate [3–5]. Air pollution can damage the brain through increased inflammation, oxidative stress, glial activation and cerebrovascular damage [9] and caused Parkinson's, Alzheimer's [4], ischemic stroke [3, 10] and mental retardation [3].

Air pollution is considered to be responsible for several million premature deaths worldwide each year [11, 12] and it is an important risk factor that threatens health in terms of shortening life span or increasing mortality [12, 13]. Air pollutants and health-related research focus mostly on single air pollutants [14, 15]. Besides this combined, air pollution from both O_3 and PM 2.5 was associated with 4.5 million deaths worldwide [13]. For example joint effects of cigarette smoking and simultaneous exposure to asbestos in lung cancer have also been reported by researchers [16, 17]. In the study examining the effects of NO_2 , PM10, SO_2 , and CO on cardiovascular diseases, only CO was associated with cardiovascular disease, ischemic heart disease, and hypertension [18].

Humans are exposed to many air pollutant particles in the inhaled air. This condition has limited results in air pollutants and disease-related research, as the effects of each pollutants cannot be measured separately. It is also difficult to determine the effects of multiple air pollutants on diseases. Besides this investigating the joint effect of multiple air pollutants effects on health has been evaluated by researchers recently [19, 20].

Studies showing the relationship between air pollutants and diseases are often carried out experimentally at the clinical level in the form of descriptive, regression and correlation studies. However, in parallel with the developing technology, public databases have been created where data on diseases are digitized. Many types of data can be accessed on these databases, such as the number of deaths from diseases, years of life lost due to diseases, incidence and prevalence of diseases. Although these data enable research from a health economics perspective using econometric methods, machine learning, and artificial intelligence algorithms, they have just begun to be researched in the literature. In the analyzes by using these methods and variables by switching from a single-pollutant approach to a multipollutant approach, better protection of public health against air pollution can be investigated. For this transition to be successful new methodological developments are needed in science's

approach to air pollution studies were pointed out in the literature [19]. Machine learning and artificial intelligence algorithms can take their place in the literature as methodologies that enable the evaluation of the joint effects of independent variables that cause disease as new approaches.

Machine learning is a branch of artificial intelligence and consists of systems that make inferences from data with mathematical and statistical operations. Today, many different machine learning methods have emerged for the inference process. These methods are classification, regression, clustering and dimension reduction [21]. A machine learning method produces an output to predict, and the produced output is called "classification" if it is categorical, and "regression" if it is numerical. Clustering is explanatory modeling, which is the process of assigning similar observations to the same clusters. Machine learning, big data, and other similar new technologies can also be used to monitor disease patterns and predict their relevance to the economy, and may offer policy-making useful information in these areas in the future. Collectively, interdisciplinary synergies in policies, geriatric care, drug development, self-awareness, big data use, machine learning and personalized medicine will be a factor that provides the most opportunities for the elderly and maximizes their longevity in the upcoming period [22]. Linear regression analysis is an important analysis tool in the machine learning approach. It aimed to establish a linear relationship between two variable groups, dependent/response and independent/predictive variables, and to estimate new values over these variables. In recent years, Multivariate linear regression method is one of the most important techniques among linear regression techniques.

Multivariate linear regression models the relation between multiple dependent variables and independent variables simultaneously. The model can be easily derived as a maximum probability estimator under the assumption that the errors are normally distributed. After all, the model has a unique global minimum that can be given explicitly. Because of its simplicity, Multivariate linear regression is considered an important analysis tool in the social and natural sciences [23]. Besides this artificial intelligence algorithms can guide in revealing the relationship between health and the environment and making effective politic decisions.

The subject of this research is the relationship between cardiovascular disease and air pollutants. Air pollution directly affects the cardiovascular system through the respiratory system. One of the significant contributors to global cardiovascular deaths is air pollution; recent analyzes estimate that CVD causes 17.9 million deaths each year [24], with one-third of these deaths occurring before 70 years of age. Cardiovascular conditions are responsible for 40–60% of premature deaths from air pollution [25, 26]. Numerous epidemiological studies have shown that cardiovascular problems caused by short-term exposure to PM increase morbidity and mortality; confirmed sensitization in older adults with CVD or diabetes [27–29]. In addition, long-term exposure to PM can greatly increase the risk of CVD;

Table 1. Defining variables

Variables	Unit	Source	Abbreviation
Particulate Matter 2.5	Kilograms per capita	https://stats.oecd.org/	PM 2.5
Non-methane volatile organic compounds	Kilograms per capita	https://stats.oecd.org/	NMVOC
The burden of cardiovascular diseases	Per capita	http://ghdx.healthdata/	CVDALY

it can reduce life expectancy by several years [30, 31]. In this context, epidemiological studies related to the cardiovascular system and air pollutants are reported frequently and provided the relationship between cardiovascular diseases and air pollutants [32–34].

This study, considering the potential of air pollution's significant health effects investigated the burden of cardiovascular disease attributable to air pollution at the Türkiye level. The European Environment Agency (EEA) stated that 97.2 percent of the urban population in Türkiye is exposed to unhealthy levels of PM10 [35]. Based on available evidence, Türkiye appears to be one of the countries in Europe with a high rate of premature deaths due to air pollution and according to current data, 28924 people died prematurely in 2010 in Türkiye due to exposure to particulate matter (PM) and ozone in the outdoor environment was indicated [36]. From this perspective to reveal air polluters' impact on the burden of cardiovascular diseases in Türkiye, the hypothesis was identified as follows:

H₁: Air pollution has been increasing the cardiovascular disease burden.

MATERIALS AND METHODS

In this section, the information about the variables used in the study, the analysis methods and tools used in the analysis, and the limitations of the study were evaluated under 3 (three) sub-headings. In this study with a different perspective, it was aimed to evaluate the relationship between cardiovascular health and air pollution using the econometric (time series analysis) and Machine Learning approaches (ML) methodology out of clinical experimental research also. First of all, it was aimed to show the effect of the joint effect of air pollutants on cardiovascular disease by defining the relationship between variables with econometric analysis, testing the obtained results through machine learning, and harmoniously evaluating the results. Therefore it is thought that the findings obtained by econometric and ML analyses at the empirical level will enrich the health-related literature in terms of methodology.

Variables

In this study, PM 2.5 and Non-Methane Volatile Organic Compounds (NMVOC) air pollutants were the independent variables; CVDALY was the dependent variable showing the deterioration in cardiovascular health and the information of the variables were given in Table 1. This study includes the regular data on PM 2.5 and NMVOC between 1990 and 2017 in Türkiye.

In the cardiovascular literature, especially PM 2.5 was studied. Particulate matter is defined according to its aerodynamic diameter. PM10 and PM 2.5 are particles smaller than 10 µm and 2.5 µm respectively. Pollutant sources that cause the formation of particulate matter; industrial processes, domestic heating processes and traffic [37].

NMVOC is a compound of many chemical species that may lead to secondary organic aerosol formation as pollutants and cause an increase in tropospheric ozone concentrations [38–40]. Some types of NMVOCs are toxic substances and can directly harm human health [41]. Disability-adjusted life years (DALY) is a health metric that measures the years of healthy life lost due to illness and injury, and it shows the sum of the years of life lost due to premature death and illness. In this study, the DALY criterion, which evaluates the years of life lost due to cardiovascular disease and the years of life spent with this disease, was used and was abbreviated as CVDALY in the study.

Statistical Analysis

Statically analyses were made under five headings. In the first section, descriptive statistics were given and the significance of the econometric model of this study was carried out by using the Least Squares Method. In the second section, unit root tests were done to determine the stationarity levels of the variables; then the lag length of the established econometric model was revealed and the causality relationships between the variables were analyzed with the Granger causality test. In the fourth section, the effect of air pollutants on cardiovascular disease burden was estimated by FMOLS and DOLS tests. In the last stage, Machine Learning Regression method was used to predict the burden of cardiovascular diseases according to the minimum level of PM 2.5 and NMVOC. The details of the methods used in the analysis and the findings obtained were given in the title of the results. The statistical analyses for econometric evaluations "Eviews 10" and for Machine Learning Approaches "Phyton" program were used.

Limitation of This Study

The year range for the data belonging to variables were between 1990 and 2017, so the time has been accepted as an important constraint for this study. Using of two variables of air pollutants (PM 2.5-NMVOC) in the study could be considered as the second limitation and the methodology used in the research was also considered as another limitation.

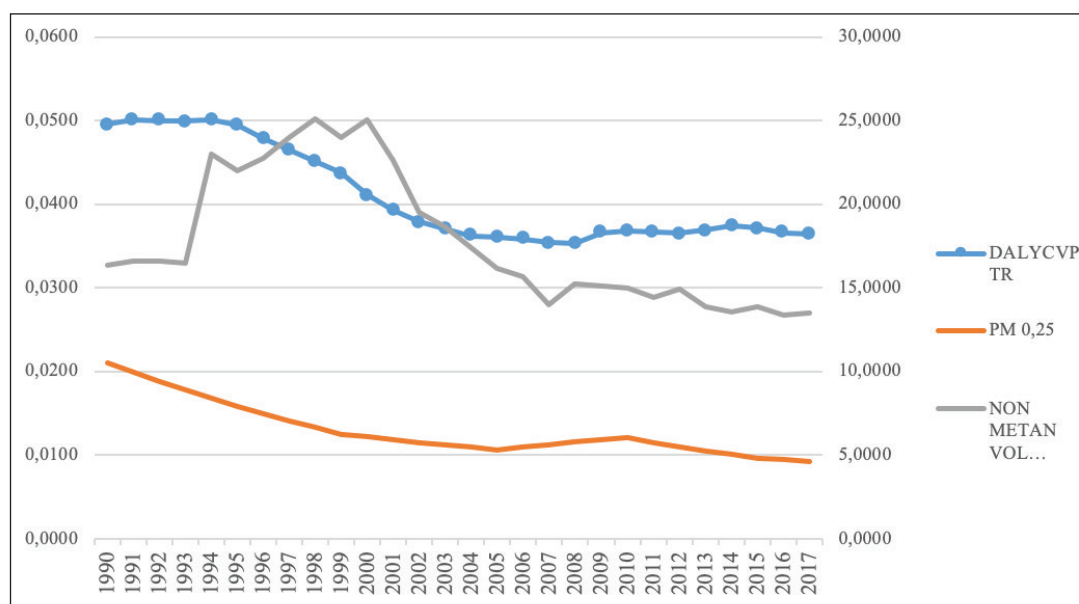


Figure 1. CVDALY, PM 2,5 and NMVOC by years, 1990–2017.

Table 2. Results of least squares

Dependent variable	Independent variable	Coefficient	Prob.	R ²	Adjusted R ²	F-statistic	Prob(F-statistic)
CVDALY	PM 2.5	0.002949	0.0000	0.8997	0.8917	112.1060	0.0000
	NMVOC	0.000412	0.0030				
	C	0.014567	0.0003				

: Significance at level 1%. Jarque Bera Normality Test: 0.261945; Ramsey Reset Test: 0.0313; Breusch-Godfrey Serial Correlation LM Test: 0.0712; Breusch-Pagan-Godfrey: 0.1354; ARCH: 0.1586 Wald Test: $c(\text{PM } 2.5)=0.002949$ $p=0.0000$ $c(\text{NMVOC})=0.000412$ $p=0.0000$.

RESULTS

CVDALY mean in Türkiye was 0.04 ± 0.01 (min: 0.03; max: 0.05); PM 2.5 mean was 6.46 ± 1.62 (min: 4.64; max: 10.48); NMVOC mean was 17.81 ± 4.01 (min: 13.38; max: 25.07) between 1990–2017 (Fig. 1).

The Econometric Model

The equation for the econometric model was set up as follows:

$$\text{CVDALY} = C(1) * \text{PM}2.5 + C(2) * \text{NMVOC} + C(3)$$

In Table 2, the value of R and R² was 89% that the explanatory power of the econometric model was good. Besides this result the relationship between the variables was found to be significant ($p < 0.01$). At the same time, diagnostic tests (Jarque Bera Normality Test; Ramsey Reset Test, Breusch-Pagan and ARCH Tests) explaining the relationship between the variables and the model confirm the significance of the model. For this reason, the model established in the study was considered significant.

Panel Unit Root Tests

In Table 3, panel unit root test results were given while null hypothesis in unit root tests indicates the existence of unit root in variables; the alternative hypothesis states that there is no unit root in the variables. In Table 3, the stationarity of the variables was found at the level.

Granger Causality Analysis

By using the Granger Panel Causality test, the causality relationship between the series has been tried to be determined. A statistically strong relationship between variables; this relationship does not mean that it means causality. The statistically, while the relationship is considered as an expression of an association, the concept of causality is primarily based on a theoretical explanation [42].

In Granger causality analysis, primarily all the series must be stationary at the same level, so the level-individual intercept model was used according to unit root test results. Then the second presumption was to determine the lag length of the model. The VAR model was set up for determine the lag lengths of the variables. In Table 3, the maximum length of the variables AIC and HQ tests were found in the 4th length and LR and SC tests were found in the 1st length and FPE tests were found in the 3rd length. Table 3 presents the results showing the delay length and the causal relationship between the estimated and predicted equation in the VAR model. The lag lengths obtained in the research were defined in the VAR Model, and since the diagnostic tests (unit root, correlation, etc.) that test the significance of the results obtained in causality analyzes were found to be significant at the 4th length, the research was carried out on the 4th lag length.

Table 3. Results of granger causality tests

A. Results of unit root tests					
Variables	Levin, Lin and Chu	Breitung t-stat	IM, Pesaran and Shin W-stat	ADF	PP
CVDALY-PM2.5-NMVOC					
Level					
Individual effects	0.0000*	–	0.0033**	0.0050**	0.0516***
Individual effects and individual linear trends	0.0109**	0.3898	0.0068**	0.0154**	0.7390
None	0.0403**	–	–	0.3091	0.0004*
1. diff.					
Individual effects	0.0255**	–	0.0063**	0.0040*	0.0034*
Individual effects and individual linear trends	0.0468**	0.0374**	0.0302**	0.0178**	0.0184**
None	0.0007*	–	–	0.0000*	0.0000*
2. diff.					
Individual effects	0.0000*	–	0.0000*	0.0000*	0.0000*
Individual effects and individual linear trends	0.0000*	0.0000*	0.0004*	0.0004*	0.0000*
None	0.0000*	–	–	0.0000*	0.0000*

*, **, ***: Significance level at 1%; 5%; 10% respectively.

B: VAR lag order selection criteria						
Lag	LogL	LR	FPE	AIC	SC	HQ
0	29.26580	NA	2.05e-05	-2.283982	-2.135874	-2.246734
1	134.3048	173.5427*	4.88e-09	-10.63520	-10.04277*	-10.48621
2	145.1050	15.02632	4.38e-09	-10.79174	-9.754983	-10.53100
3	156.8363	13.26153	3.92e-09*	-11.02925	-9.548168	-10.65676
4	167.8489	9.576110	4.29e-09	-11.2042*	-9.278847	-10.72002*
5	175.7811	4.828307	7.98e-09	-11.11140	-8.741672	-10.51542

*: Indicates lag order selected by the criterion; LR: Sequential modified LR test statistic (each test at 5% level); FPE: Final prediction error; AIC: Akaike information criterion; SC: Schwarz information criterion; HQ: Hannan-Quinn information criterion.

C: Granger causality/block exogeneity wald tests				
Nul hypothesis	Prob.	Condition	Description	
PM 2.5 \Rightarrow CVDALY	0.0001*	Rejected	PM 2.5 was the Granger cause of the CVDALY	
NMVOC \Rightarrow CVDALY	0.0000*	Rejected	NMVOC was the Granger cause of the CVDALY	
CVDALY \Rightarrow PM 2.5	0.7006	Received	CVDALY was not the Granger cause of the PM 2.5	
NMVOC \Rightarrow PM 2.5	0.9953	Received	NMVOC was not the Granger cause of the PM 2.5	
CVDALY \Rightarrow NMVOC	0.0513	Received	CVDALY was not the Granger cause of the NMVOC	
PM 2.5 \Rightarrow NMVOC	0.3813	Received	PM 2.5 was not the Granger cause of the NMVOC	

JB Normality test:0.9497; VAR Residual Serial Correlation LM Tests:0.6430; VAR satisfies the stability condition between 0.180447–0.923563; * significance level at 1% and in the estimation 4th lag length was used.

Johansen Cointegration Test

The effects of air pollutants on the cell epithelium take time depending on the intensity of exposure to the agent. The effects of continuous and small amounts of exposure appear in many years. Especially in chronic diseases, diseases develop in the long term due to exposure to the agent. It should not be ignored that questioning long-term relationships through cointegration tests will also provide important evidence in the

analyses carried out on these diseases and their factors. From this perspective having verified that the series were nonstationary and same order integration as $I(0)$, it was tested whether there exists any long-run equilibrium relationship between the variables by using Johansen cointegration tests (Table 4). According to the Johansen cointegration result there was at least one cointegration relationship between variables; that showed CVDALY- PM 2.5-NMVOC acts together in the long term.

Table 4. Cointegration –DOLS-FMOLS test results

A. Johansen Cointegration Test Results				
Unrestricted cointegration rank test (trace)	Eigenvalue	Trace statistic	Critical value	Prob
No deterministic trend - Lags interval (in first differences): 1 to 4				
None*	0.5848	39.6065	35.1927	0.0157*
At most 1	0.4560	19.3871	20.2618	0.0656**
At most 1	0.2086	5.3835	9.1645	0.2440
Linear deterministic trend - Lags interval (in first differences): 1 to 4				
None*	0.5413	31.6934	29.7970	0.0299*
At most 1	0.4432	13.7669	15.4947	0.0896**
At most 1	0.0128	0.29855	3.8414	0.5848

*, **: Significance level at 5%; 10% respectively. JB Normality test: 0.013; VAR Residual Serial Correlation LM Tests: 0.9011; VAR Residual Heteroskedasticity Tests: 0.6945; VAR satisfies the stability condition between 0.225647–0.897363.

B: Panel DOLS and FMOLS estimations results**The dependent variable: CVDALY**

	DOLS		FMOLS	
	Coefficient	t-Statistic	Coefficient	t-Statistic
PM 2.5	0.002122 (0.0000)	9.697258	0.002703 (0.0000)	8.482802
NMVOC	0.000249 (0.0002)	4.733593	0.000362 (0.0037)	3.220116
	R: 0.99 R ² : 0.98		R: 0.88 R ² : 0.87	
	JB Normality test 0.5143		JB Normality test 0.2487	

Notes: Probability values are in parenthesis. In the DOLS estimation method, lead and lag were set as 1.

Dynamic Least Square (DOLS)-Fully Modified Ordinary Least Square (FMOLS) Tests

Panel DOLS and FMOLS tests are commonly used tests in cointegrated panel tests. In this study, the relationship between variables was estimated using dynamic least squares (DOLS) and fully modified ordinary least squares (FMOLS) techniques (Table 4).

According to the DOLS coefficient estimation results, PM 2.5 and NMVOC were effective on CVDALY positively and 1 unit increase in PM 2.5 increased CVDALY by 0.0021 units; 1 unit increase in NMVOC increased CVDALY by 0.00024 units ($p < 0.00$). According to the FMOLS coefficient estimation results, PM 2.5 and NMVOC were effective on CVDALY and 1 unit increase in PM 2.5 increased CVDALY by 0.0027 units; 1 unit increase in NMVOC increased CVDALY by 0.00036 units ($p < 0.00$). In summary, the main findings obtained from FMOLS and DOLS forecasting methods confirm the positive impact of PM 2.5 and NMVOC effective on CVDALY.

Machine Learning Method

This study tried to determine the independent variables (PM 2.5 -NMVOC) effects on the dependent variable

(CVDALY) by using the ML method. The Least Squares Method results by using the ML approach was shown in Table 5. According to Table 5, the dependent and independent variables' coefficients gave consistent results with econometric results as in Table 2 and Table 4.

According to the ML estimation result, PM 2.5 and NMVOC were effective on CVDALY, and 1 unit increase in PM 2.5 increased CVDALY by 0.0029 units; 1 unit increase in NMVOC increased CVDALY by 0.0004 units. In summary, the main findings obtained from ML forecasting methods confirm the positive impact PM 2.5 and NMVOC effective on CVDALY as the results of the econometric model (Table 4).

Regression analyses provided important evidence in revealing the relationship between the dependent and independent variables, but evaluations made within the framework of this evidence may lead to more rough estimates. However methods such as ML approaches have only just begun to be studied in the literature, they could be helpful to determine the joint effect of independent variables on the dependent variable. As a matter of fact, in this study, the ML method was used to determine the joint effect of PM 2.5 and NMVOC on CVDALY.

Table 5. OLS results by machine learning method

Dependent variable	Independent variable	Coefficient	Prob.	R ²	Adjusted R ²	F-Statistic	Prob(F-statistic)
CVDALY	PM 2.5	0.0029 (0.000)	0.0000*	0.900	0.892	112.8	3.07e-13
	NM VOC	0.0004 (9.48e-05)	0.0000*				
	C	0.0146 (0.002)	0.0000*				

Jarque Bera Normality Test: 2.650; *: Significance level at 1%.

B: Machine learning regression estimations results

PM 2.5	=0.84
NM VOC	=9.48
CVDALY ML estimation value	=0.02206693
Multi Regression Score	0.8966072524192289
r2 socre	0.8966072524192289
MAE	0.0018798910197996026
RMSE	0.0019494894486548
Explain Varians Score	0.8797690050363055

Omnibus: 12.505 Durbin-Watson: 0.312; Prob(Omnibus): 0.002 Jarque-Bera (JB): 2.650. Skew: 0.190 Prob (JB): 0.266; Kurtosis: 1.542.

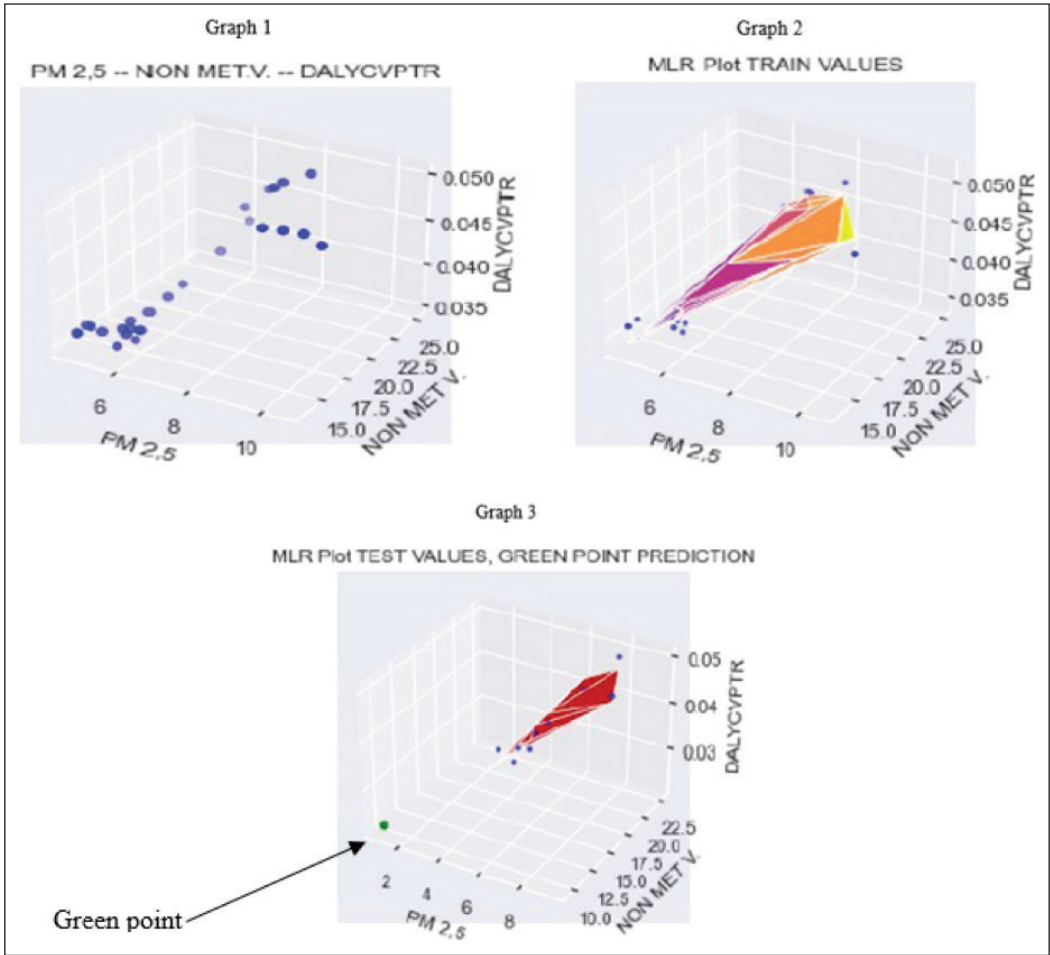


Figure 2. CVDALY-PM 2.5 – NMVOC MLregression model.

In the study, regression analyses showed that PM 2.5 and NMVOC increased CVDALY. Therefore by using the ML methods to find the answer to the question that how CVDALY would be affected as a result of reducing these two air pollutants together; first of all, assuming that it was not possible to completely destroy the particles in the air, it was thought that it would be appropriate to determine the country where the particles in the study were at the lowest level for the analysis. As a matter of fact, the country with the lowest values of PM 2.5 and NMVOC in 2017 among the countries with data on air pollutants was Sweden. When to defined these values to the ML method -the current PM 2.5 (4.64) and NMVOC (13.49) value in Türkiye was reduced to Swedens' PM 2.5 (0.84) and NMVOC (9.48) values- CVDALY was decreased from 0.0364 to 0.022 in Türkiye (Table 5 section B). In other words, ML approaches results showed that in Türkiye reducing PM 2.5 by about 4.5 times and NMVOC by about 30% would be reduced CVDALY by about 39.6%.

In Figure 2, the first graph shows the regression relationship between the variables; while revealing the relationship of independent variables with the dependent variable perly in the second graph; the point indicated as green in the 3rd graph showed the joint effect of the reduced PM 2.5 and NMVOC value together on CVDALY.

DISCUSSION

In this study, PM_{2.5} and NMVOC air pollutants were discussed in order to determine the effect of air pollution on cardiovascular diseases in Türkiye. In this context, data from the years 1990–2017 were used. In general, while the CVDALY has decreased by approximately 27% from 2017 to 1990; PM_{0.25} and NMVOC also decreased by 56%, and 17% respectively. In econometric evaluation, the unidirectional Granger causality relationship from PM 2.5 to CVDALY; and the unidirectional Granger causality relationship from NMVOC to CVDALY were revealed. The cointegration test results show the long-term relationships between PM 2.5 - NMVOC -CVDALY as showing long term relationships. Generally, a 1 unit increase in PM 2.5 increased CVDALY by between 0.0021–0.0029 units; a 1 unit increase in NMVOC increased CVDALY by between 0.00024–0.0004 units. ML approach results showed that in Türkiye reducing PM 2.5 by about 4.5 times and NMVOC by about 30% would reduce CVDALY by about 39.6% (reduced to Swedens' air polluter values). Within the framework of these findings the hypothesis identified as "Air pollution has been increasing the cardiovascular disease burden" was received in this study.

A research project involving 25 European cities has shown that complying with the WHO's 10 µg/m³ standard for average annual PM 2.5 concentration may increase the average life expectancy of people aged 30 and over by up to 22 months [43]. Estimates, based on further analysis of the concentration of particles in the air, predict that deaths, particularly from outdoor air pollution, may reach up to 8.9 million in a year [25] and estimated that reducing air pollution to WHO air quality guidelines worldwide will increase life expectancy by 0.6 years [12].

In Australia, a 38% reduction in PM₁₀ led to a 17.9% reduction in cardiovascular diseases and a 22.8% reduction in respiratory diseases, and an 11.4% reduction in overall mortality. In addition, it has been shown that this decrease is more effective with a 19.6% decrease in cardiovascular diseases and a 22.9% decrease in respiratory diseases in winter [44]. The ban on coal burning in Durbin Ireland resulted in a 71% reduction in black smoke dust (smoke) and a 34% reduction in sulfur dioxide in the air, and this reduction caused decrease in cardiovascular disease by 7%, respiratory disease by 13% and overall mortality by 8% in this city [45].

CONCLUSION

The results obtained from this study confirmed the relationship between air pollutants and the burden of cardiovascular diseases. PM 2.5 and NMVOC are foreseen as significant threats to public health and showed the need to reduce air pollutants which are one of the causes of the burden of cardiovascular diseases in Türkiye.

Besides this, the analysis of data using the econometric methodology and machine learning approaches also showed that it is possible to evaluate the health-related literature, which was studied in experimental clinic research, from out of the clinic with a different perspective. Therefore the use of econometric and machine learning models to monitor disease models and predict their relationship to the burden of diseases can guide the development of health policies. Therefore it is also thought that this study will contribute to the health and artificial intelligence-related literature. However, it should be noted that there are uncertainties in assessing the health effects of multiple air pollutants arising from various factors such as econometric calculations, measurement errors, and the degree of relationships between pollutants. It is also worth noting that more epidemiological studies are needed to verify whether econometric models and ML approaches are reliable.

ACKNOWLEDGEMENTS

Author would like to thank I.B. for the technical reading and Ö.S. for the analysis of ML Approaches in the study.

DATA AVAILABILITY STATEMENT

The author confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

REFERENCES

- [1] D. B. Resnik, and C. J. Portier, "Environment and Health," in *From Birth to Death and Bench to Clinic: The Hastings Center Bioethics Briefing Book for Journalists, Policymakers, and Campaigns*, M. Crowley, Ed. Garrison, NY: The Hastings Center, 2008, pp. 59–62.
- [2] T. D. Nelin, A. M. Joseph, M. W. Gorr, and L. E. Wold, "Direct and indirect effects of particulate matter on the cardiovascular system," *Toxicology Letters*, Vol. 208, pp. 293–299, 2012. [CrossRef]
- [3] Ö. Cavkaytar, Ö. Ü. Soyer, and B. E. Şekerel, "Türkiye'de hava kirliliğinden kaynaklanan sağlık sorunları," *Hava Kirliliği Araştırmaları Dergisi*, Vol. 2, pp. 105–111, 2013.
- [4] Ç. Güler, and Z. Çobanoğlu, "Çevresel etkenlere bağlı olarak ortaya çıkan Hastalıklar," (1st ed.), T.C. Sağlık Bakanlığı Yayınları, 1994,
- [5] E. Kardeşoğlu, M. Yalçın, and Z. Işılak, "Hava kirliliği ve kardiyovasküler sistem," *TAF Preventive Medicine Bulletin*, Vol. 10(1), pp. 97–106, 2011.
- [6] M. R. Miller, E. David, and Newby, "Air pollution and cardiovascular disease: car sick," *Cardiovascular Research*, Vol. 116, pp. 279–294, 2020. [CrossRef]
- [7] I. Mordukhovich, B. Coull, I. Kloog, P. Koutrakis, P. Vokonas, and J. Schwartz, "Exposure to sub-chronic and long-term particulate air pollution and heart rate variability in an elderly cohort: the Normative Aging Study," *Environmental Health*, Vol. 14, Article 87, 2015. [CrossRef]
- [8] F. Wang, Q. Liang, M. Sun, Y. Ma, L. Lin, T. Li, J. Duan, and Z. Sun, "The relationship between exposure to PM_{2.5} and heart rate variability in older adults: A systematic review and meta-analysis," *Chemosphere*, Vol. 261, 2020. [CrossRef]
- [9] S. Genç, Z. Zadeoglulari, S. H. Fuss, and K. Genc, "The adverse effects of air pollution on the nervous system," *Journal of Toxicology*, Vol. 2012, Article 782462, 2012. [CrossRef]
- [10] Y. C. Hong, J. T. Lee, H. Kim, and H. J. Kwon, "Air pollution: a new risk factor in ischemic stroke mortality," *Stroke*, Vol. 33, pp. 2165–2169, 2002. [CrossRef]
- [11] World Health Organization, "Air Quality and Health," WHO Factsheets, 2011. <http://www.who.int/mediacentre/factsheets/fs313/en/>.
- [12] J. S. Apte, M. Brauer, A. Cohen, M. Ezzati, and C. A. Pope, "Ambient PM_{2.5} reduces global and regional life expectancy," *Environmental Science & Technology Letters*, Vol. 5, pp. 546–551, 2018. [CrossRef]
- [13] A. J. Cohen, M. Brauer, R. Burnett, H. R. Anderson, J. Frostad, and K. Estep, "Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the Global Burden of Diseases Study 2015," *Lancet*, Vol. 389(10082), pp. 1907–1918, 2017. [CrossRef]
- [14] M. L. Bell, J. Y. Kim, and F. Dominici, "Potential confounding of particulate matter on the short-term association between ozone and mortality in multisite time-series studies," *Environmental Health Perspectives*, Vol. 115(11), pp. 1591–1595, 2006. [CrossRef]
- [15] R. Rojas-Martinez, R. Perez-Padilla, G. Olaiz-Fernandez, L. Mendoza-Alvarado, H. Moreno-Macias, T. Fortoul, W. McDonnell, D. Loomis, and I. Romieu, "Lung function growth in children with long-term exposure to air pollutants in Mexico City," *American Journal of Respiratory and Critical Care Medicine*, Vol. 176, pp. 377–385, 2007. [CrossRef]
- [16] T. C. Erren, M. Jacobsen, and C. Piekarski, "Synergy between asbestos and smoking on lung cancer risks," *Epidemiology*, Vol. 10, pp. 405–411, 1999. [CrossRef]
- [17] D. W. Henderson, K. Rödelberger, H. J. Weitowitz, and J. Leigh, "After Helsinki: a multidisciplinary review of the relationship between asbestos exposure and lung cancer, with emphasis on studies published during 1997–2004," *Pathology*, Vol. 36, pp. 517–550, 2004. [CrossRef]
- [18] L. Sokoty, S. Rimaz, B. Hassanlouei, A. R. Mohammadi, F. Zayeri, H. Parsaeian, "Short-term effects of air pollutants on hospitalization rate in patients with cardiovascular disease: a case-crossover study," *Environmental Science and Pollution Research*, Vol. 28, pp. 26124–26131, 2021. [CrossRef]
- [19] F. Dominici, R. D. Peng, C. D. Barr, and M. L. Bell, "Protecting human health from air pollution: shifting from a single-pollutant to a multipollutant approach," *Epidemiology*, Vol. 21(2), pp. 187–194, 2010. [CrossRef]
- [20] Y. Zhu, Y. Wang, H. Xu, B. Luo, W. Zhang, B. Guo, S. Chen, X. Zhao, and W. Li, "Joint effect of multiple air pollutants on daily emergency department visits in Chengdu, China," *Environmental Pollution*, Vol. 257, Article 113548, 2020. [CrossRef]
- [21] E. Önder, "Sağlıkta gelişmekte olan teknolojiler, yapay zeka ve r ile makine öğrenimi uygulamaları," Dora Yayınları, 2020.
- [22] E. F. Fang, M. Scheibye-Knudsen, H. J. Jahn, J. Li, L. Ling, and H. Guo, "A research agenda for aging in China in the 21st century," *Ageing Research Reviews*, Vol. 24, pp. 197–205, 2015. [CrossRef]
- [23] Y. Su, X. L. Gao, and D. Tao, "Multivariate multilinear regression," *IEEE Transactions on Systems, Man, and Cybernetics, Part B (Cybernetics)*, Vol. 42(6), pp. 1560–1573, 2012. [CrossRef]
- [24] World Health Organization, "Cardiovascular diseases," [https://www.who.int/en/news-room/factsheets/detail/cardiovascular-diseases-\(cvds\)](https://www.who.int/en/news-room/factsheets/detail/cardiovascular-diseases-(cvds)). Accessed on May 17, 2019.
- [25] R. Burnett, H. Chen, M. Szyszkowicz, and J. V. Spadaro, "Global estimates of mortality associated with long-term exposure to outdoor fine particulate matter," *Proceedings of the National Academy of Sciences of the United States of America*, Vol. 115, pp. 9592–9597, 2018. [CrossRef]

- [26] M. R. Miller, and D. E. Newby, “Air pollution and cardiovascular disease: car sick,” *Cardiovascular Research*, Vol. 116(2), pp. 279–294, 2020. [CrossRef]
- [27] Q. Di, I. Dai, Y. Wang, A. Zanobetti, C. Choirat, J. D. Schwartz, and F. Dominici, “Association of short-term exposure to air pollution with mortality in older adults,” *JAMA*, Vol. 318(24), pp. 2446–2456, 2017. [CrossRef]
- [28] M. Baccini, A. Mattei, F. Mealli, P. A. Bertazzi, and M. Carugno, “Assessing the short-term impact of air pollution on mortality: a matching approach,” *Environmental Health*, Vol. 16(1), Article 7, 2017. [CrossRef]
- [29] R. Ruckerl, A. Schneider, S. Breitner, J. Cyrys, and A. Peters, “Health effects of particulate air pollution: a review of epidemiological evidence,” *Inhalation Toxicology*, Vol. 23, pp. 555–592, 2011. [CrossRef]
- [30] R. D. Brook, S. Rajagopalan, C. A. Pope 3rd, J. R. Brook, A. Bhatnagar, A. V. Diez-Roux, “Particulate matter air pollution and cardiovascular disease: an update to the scientific statement from the American heart association,” *Circulation*, Vol. 12, pp. 2331–2378, 2010. [CrossRef]
- [31] G. Cesaroni, C. Badaloni, C. Gariazzo, M. Stafoggia, R. Sozzi, M. Davoli, and F. Forastiere, “Long-term exposure to urban air pollution and mortality in a cohort of more than a million adults in Rome,” *Environmental Health Perspectives*, Vol. 121(3), pp. 324–331, 2013. [CrossRef]
- [32] P. L. Ljungman, and M. A. Mittleman, “Ambient air pollution and stroke,” *Stroke*, Vol. 45(12), pp. 3734–3741, 2014. [CrossRef]
- [33] W. S. Yang, X. Wang, Q. Deng, W. Y. Fan, and W. Y. Wang, “An evidence-based appraisal of global association between air pollution and risk of stroke,” *The International Journal of Cardiology*, Vol. 175(2), pp. 307–313, 2014. [CrossRef]
- [34] A. S. Shah, K. K. Lee, D. A. McAllister, A. Hunter, H. Nair, W. Whiteley, J. P. Langrish, D. E. Newby, and N. L. Mills, “Short-term exposure to air pollution and stroke: systematic review and meta-analysis,” *BMJ*, Vol. 350, Article h1295, 2015. [CrossRef]
- [35] EEA, “Air Pollution Country Factsheet: Turkey, 2014,” <http://www.eea.europa.eu/themes/air/air-pollution-country-fact-sheets2014/turkey-air-pollutant-emissions-country-factsheet/view>
- [36] Brief report, “Air Pollution and Health in Turkey: Facts, Figures, and Recommendations,” https://env-health.org/IMG/pdf/150220_factsheet_air_and_health_turkey_en_final.pdf.
- [37] EC, “Cleaner air for all,” http://ec.europa.eu/environment/air/cleaner_air. Accessed on 05 Apr, 2017.
- [38] EEA, “Air quality in Europe – 2015 report,” European Environment Agency, EEA report no. 5/2015, <http://www.eea.europa.eu/publications/air-quality-in-europe-2015>. Accessed on Mar 6, 2016.
- [39] A. B. Guenther, M. Jiang, C. Heald, Sakulyanontvitaya, T. Duhl, Emmons, and J. Wang, “The Model of Emissions of Gases and Aerosols from Nature version 2.1 (MEGAN2.1): an extended and updated framework for modeling biogenic emissions,” *Geoscientific Model Development Discussions*, Vol. 5, pp. 1471–1492, 2012. [CrossRef]
- [40] S. D. Piccot, J. J. Watson, and J. W. Jones, “A global inventory of volatile organic compound emissions from anthropogenic sources,” *Journal of Geophysical Research: Atmospheres*, Vol. 97, pp. 9897–9912, 1992. [CrossRef]
- [41] S. Weichenthal, R. Kulka, P. Bélisle, L. Joseph, A. Dubeau, C. Martin, D. Wang, and R. Dales, “Personal exposure to specific volatile organic compounds and acute changes in lung function and heart rate variability among urban cyclists,” *Environmental Research*, Vol. 118, pp. 118–123, 2012. [CrossRef]
- [42] C. W. Granger, “Investigating causal relations by econometric models and cross-spectral methods,” *Econometrica*, Vol. 37(3), pp. 424–438, 1969. [CrossRef]
- [43] “Summary report of the Aphekom project 2008–2011,” www.aphekom.org. Accessed on Jan 8, 2023.
- [44] F. H. Johnston, I. C. Hanigan, S. B. Henderson, and G. G. Morgan, “Evaluation of interventions to reduce air pollution from biomass smoke on mortality in Launceston, Australia: retrospective analysis of daily mortality, 1994–2007,” *British Medical Journal*, Vol. 346, Article e8446, 2013. [CrossRef]
- [45] L. Clancy, P. Goodman, H. Sinclair, and D. W. Dockery, “Effect of air-pollution control on death rates in Dublin, Ireland: an intervention study,” *Lancet*, Vol. 360(9341), pp. 1210–1214, 2002. [CrossRef]



Research Article

The biodiversity and conservation assessment of Bamui beel in Bangladesh: Current status and threats

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ARTICLE INFO

Article history

Received: 24 October 2023

Revised: 27 November 2023

Accepted: 28 December 2023

Key words:

Biodiversity; Bamui beel,
Conservation; Diversity index;
IUCN

ABSTRACT

A year-long research was conducted with a novel purpose for categorizing and documenting the existing fish diversity and abundance of Bamui beel in Jamalpur district located in Northeast part of Bangladesh, within a time frame from July 2022 to June 2023. A total of 46 fish species were identified that belonged to 18 taxonomical families and 8 orders. The most abundant family was Cyprinidae (25%). Among 46 species, 37% were commonly available (CA) and 11% were abundantly available (AA) in terms of biodiversity status. According to the global conservational status, around 74% were reported as least concerned (LC) whereas 4% were nearly threatened (NT). On the other hand, in consonance with the conservational status of Bangladesh 52% were least concerned (LC) and 11% were endangered (EN). Pielou's evenness score in Bamui beel was the highest (0.247) in pre-monsoon and the lowest (0.213) in monsoon. Shannon-Weaver diversity index was ranged from 1.992 to 2.114, whereas Simpson's dominance index value was a maximum of 0.883 in pre-monsoon and a minimum of 0.852 in monsoon. The yearly fish production of the beel was 7.023 metric tons during experimental year. Besides this, small indigenous species (SIS) of fish dominated with 63.34% of the beel's species makeup. Nevertheless, the abundance and diversity of fish species are diminishing daily in this beel. For preserving the fish diversity of Bamui beel calls for the implementation of effective fishery management practices, vigilant monitoring to prevent overfishing, and a strong emphasis on raising awareness among fishermen.

Cite this article as: Mia R, Rahman M, Chowdhury A, Ahammad B, Samanta Chandan CS, Majumdar BC, Akter S, Rahma Z. The biodiversity and conservation assessment of Bamui beel in Bangladesh: Current status and threats. Environ Res Tec 2024;7(1)71–82.

INTRODUCTION

Bangladesh is plentiful and blessed with huge and rich fisheries resources that are enriched and diverse with 260 freshwater indigenous fish species that belong to 145 genera

and 55 families that constitute the most diverse fish biodiversity ever documented [1–3]. Bangladesh is a riverine country with numerous rivers, canals, floodplains, ponds, beels, haors, reservoirs, artificial lakes, and a long coastline with estuaries [4–6]. One of the top nations in the world

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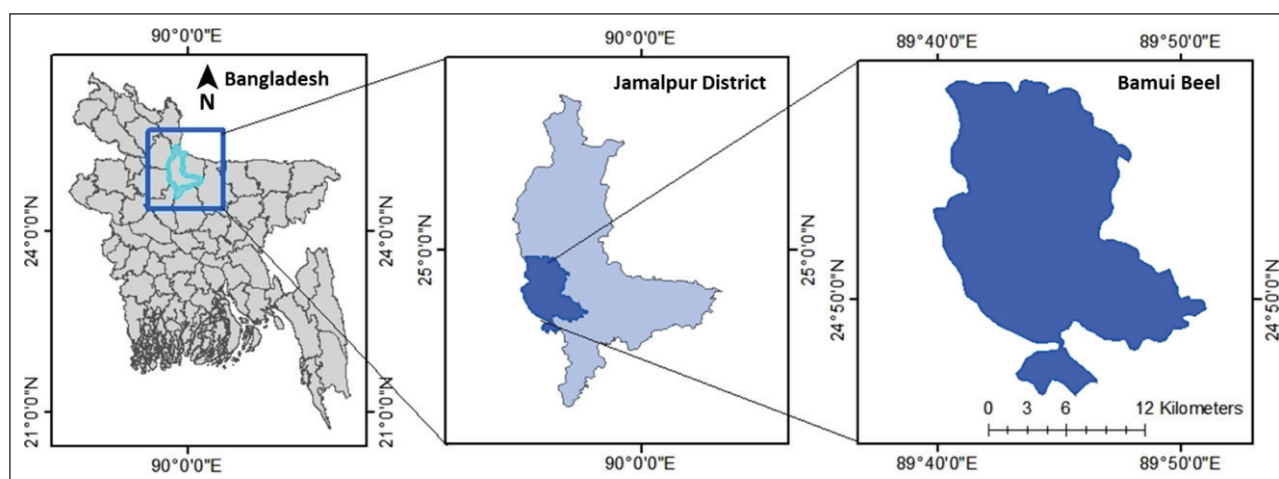


Figure 1. Map depicting the study area of Bamui *beel* in Bangladesh (89.42°12'35" E Longitude and 24.50°10'87" N Latitude).

for fish production is a country named Bangladesh [7]. Bangladesh ranked fifth in the world and third in Asia in aquaculture production in 2019 [8]. In Bangladeshi diets, fish alone provides over 63% of animal protein and many of other important vitamins and minerals [9–11]. Major subsistence and commercial fishing are supported by *haors* and *beels*, while extensive aquatic flora from those ecosystems provides rich grazing for domestic cattle, as well as fuel and fertilizer for the local purposes [12]. Environmental, sociological, and commercial dynamics link with biotic and abiotic components, particularly people and are useful in protecting aquatic habitats as a part of nature [13]. The significant decline in natural fish habitats and global biodiversity has elevated the exploration of heterogeneity as a primary focus for fisheries scientists. Genetic taxa, assemblages, ecosystems, and essential features should be considered in biodiversity experiments for assessing diversity and conservational status [14]. Besides, Bangladesh has a substantial capture rate due to its extensive river systems. The favorable topographical position and climatic conditions have facilitated the capture fishing and aquaculture potential of that nation [15]. The Bengali word "*beel*" refers to a static, rather large water body that collects run-off through an internal drainage canal. In low-lying floodplain regions of Bangladesh, this kind of seasonal and shallow water body is typical [16]. *Beel* covers about 114,161 acres, or 27.0% of inland freshwater of Bangladesh [17]. A *beel* becomes a very large water body in the monsoon and primarily dries out in the post-monsoon season because it absorbs surface run-off water from rivers and channels (Khal) [18–20]. But in the past 150 years, wetlands across the world have changed, degraded and/or perhaps disappeared up to 50% because of climate change, population increase, urbanization, conversion to agricultural field and others [21]. Developing nations like Bangladesh already perceived the importance of keeping an eye on biodiversity in protected regions [22].

Regrettably, encroachment and ecological pollution, which includes activities like renovating embankment structures, have posed a significant threat to freshwater ecosystems. Additionally, the degradation caused by sewage, commer-

cial waste, agricultural litter, and drainage has contributed to the decline of a substantial number of aquatic species [13]. The diversity indexes are useful methods that offer crucial data on the status of species variation found in a water body [23]. A few researches have been carried out to determine the diversity of fish and fish-related other aquatic organisms in Bangladesh [24, 25]. In Bangladesh, several researches have been conducted for the greater biodiversity of *beel* fisheries, including Chalan *beel* [26], Gharial *beel* [20], Chanda *beel* [27] and Kawadighi *beel* [28] to name some. The Chalan *beel* species diversity is shrinking continuously, mainly because of the deterioration of the water quality due to pollution, exploitation, improper use of crop pesticides and uncontrolled over-fishing [26].

Up to date, no research has been conducted yet on the fisheries biodiversity status of the Bamui *beel*. Therefore, this would be the first documentation of fish biodiversity for that inland waterbody. This experiment was mainly focused on the documentation of fishes and prawns available and also entails the threats and condition of aquatic biodiversity in the Bamui *beel* of Bangladesh.

MATERIALS AND METHODS

Study Area and Time Frame

The experiment was conducted at Bamui *beel* within the Jamalpur Sadar upazilla at approximately between the 89.42°12'35" E Longitude and 24.50°10'87" N Latitude in the Jamalpur district under the Mymensingh division of Bangladesh. This water body is situated 5.5 kilometers away from Dighait Bazar and is placed directly beside the Tangail-Jamalpur highway. The Bamui *beel* is connected with the Bangshi river (Fig. 1). Data were collected from the selected areas during the months of July 2022 to June 2023.

Water Quality Parameters

A number of clear 500 ml marked black bottles were used for collection of water samples. Then water samples were taken in the vial immediately after sample collection at the site. Different analyses were done by using an YSI digital wa-

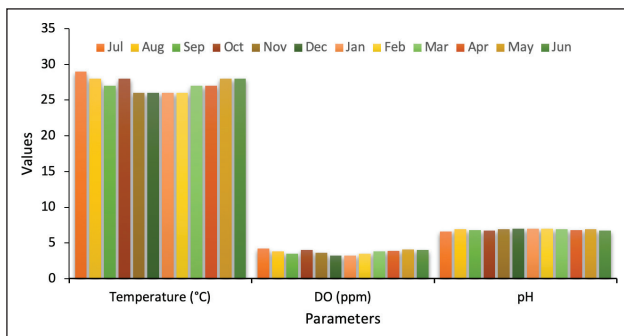


Figure 2. Month-wise water quality parameters of Bamui beel from July 2022 to June 2023.

ter quality multimeter (USA) for determining the value of water parameters (Temperature, Dissolved oxygen and pH).

Data Collection

Before collecting the necessary data, a questionnaire was prepared which was checked and verified by biodiversity experts. All data were collected by the research personnel himself using personal interviews from local fish farmers (n=357). Fish sampling was carried out at various locations with the assistance of fishermen by utilizing traditional fishing techniques with a variety of nets (gill nets, cast nets, and drag nets) and from nearby local fish markets adjacent to the *beel*. The data was collected from both primary and secondary sources. The researchers personally gathered the primary data from fishermen. Around 3 field visits per month were made to collect water quality parameters and detailed information on aquatic fauna with high biological diversity.

Biodiversity Status Analysis

Different diversity indexes were calculated to analyze the fish diversity including Simpson's dominance index (D), Pielou's evenness index (J'), and Shannon-Weaver diversity index (H).

The above-mentioned diversity indexes were calculated using the following formula [29]. Shannon-Weaver Diversity Index:

$$H = -\sum P_i(\ln P_i)$$

Here, P_i is the relative abundance (s/N) and H is the diversity index. Shannon-Weaver variation is a popular metric for assessing the degree of variety among many habitats. Simpson's Dominance Index:

$$D = \{\sum n(n-1)/N(N-1)\}$$

The calculation of habitat biodiversity, considering both the overall species count and their proportional representation, was typically performed utilizing the following equation [30]. Pielou's Evenness Index:

$$J' = H/\ln S$$

Here, S is the total number of species, \ln is the natural logarithm, J' is the similarity or evenness index, and H' is the Shannon-Weaver index. The probability that two in-

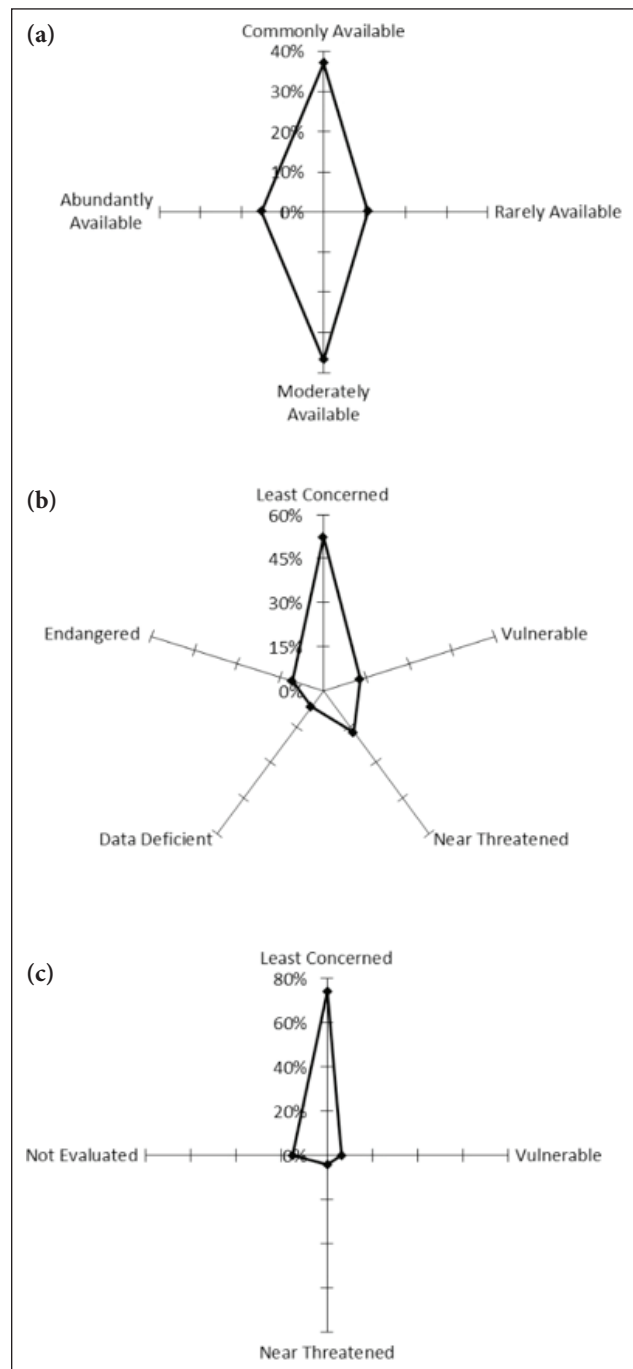


Figure 3. (a) Present status of fish species in Bamui *beel*, (b) Conservational status according to Bangladesh, (c) Global conservation status of existing species.

dividuals, picked randomly and separately from a population would belong to different species was represented by Pielou's evenness index [31].

Statistical Analysis

All the data were accumulated to analyze the findings. Tabular technique was applied by using simple statistical tools such as percentages and averages. For processing and analyzing the data "Microsoft Office 2019" and "IBM SPSS 26" were used, finally presented through textual, tabular and graphical format for better understanding.

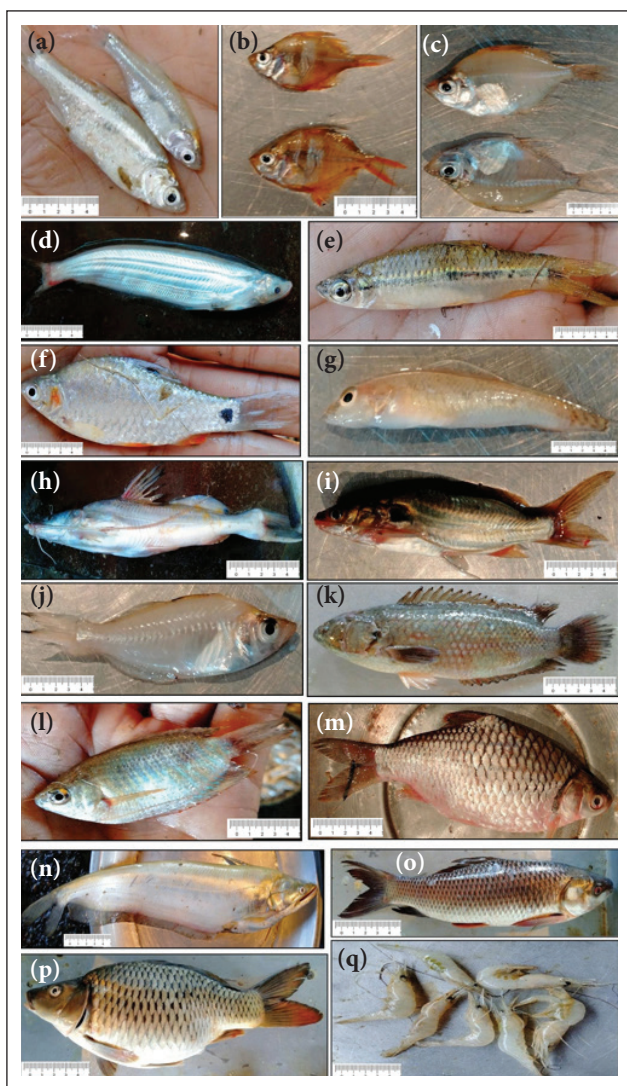


Figure 4. Some important fish species in the Bamui beel according to the conservational status of Bangladesh: (a) *Amblypharyngodon mola*, (b) *Chanda lala*, (c) *Chanda beculis*, (d) *Ompok pabo*, (e) *Esomus danricus*, (f) *Pethia ticto*, (g) *Glosogobius giuris*, (h) *Sperata aor*, (i) *Mystus vittatus*, (j) *Chanda nama*, (k) *Anabas testudineus*, (l) *Trichogaster fasciata*, (m) *Barbodes sarana*, (n) *Wallago attu*, (o) *Labeo rohita*, (p) *Cyprinus carpio*, (q) *Solenocera crassicornis*.

RESULTS AND DISCUSSION

Water Quality Parameters

Water quality parameters like temperature, dissolved oxygen (DO) and pH of the study area are presented in (Fig. 2) throughout the study period. The average highest temperature and DO of the beel was found in the month of July and pH was found in the months of December to February.

Fish Biodiversity and Conservational Status of Bamui Beel

Top ten mostly abundant fish species prior to its availability of Bamui beel has been enlisted during the experiment (Table 1). Additionally, seven different species of carp were identified in the study. Among them *Labeo rohita*, *Labeo calbasu*, *Ctenopharyngodon idella*, *Cyprinus carpio* and

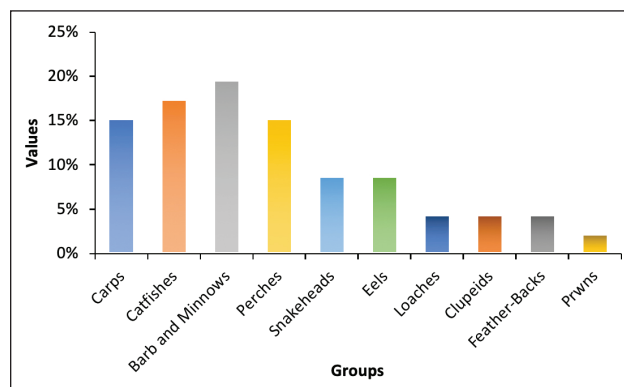


Figure 5. Status of different fish groups in the Bamui beel.

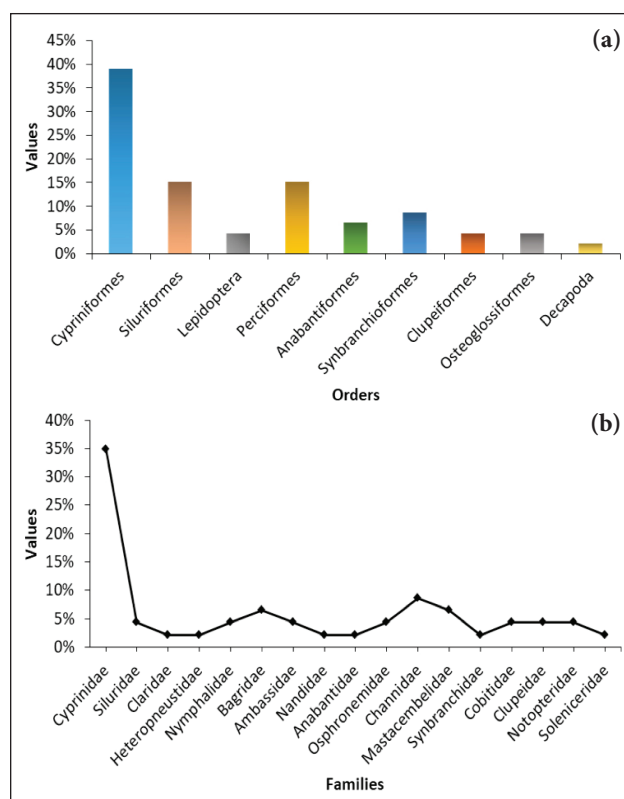


Figure 6. Fish species in the Bamui beel under different (a) order and (b) families.

Labeo gonius were moderately available (MA) (Fig. 3). Rest of the carp species were commonly available (CA). During the research period, eight (08) different species of catfish were found in the Bamui beel. *Wallago attu*, *Ompok pabo*, *Heteropneustes fossilis* and *Sperata aor* were commonly available (CA) of catfish while *Pseudotropheus atherinoides*, *Mystus bleekeri* and *Mystus vittatus* were abundantly available (AA). On the other hand, *Clarias batrachus* was moderately available (Fig. 3). Additionally, nine (09) different species of barbs and minnows were recorded. Among different types of Barbs and Minnows, *Puntius ticto*, *Puntius sophore*, *Puntius guganio* and *Amblypharyngodon mola* were abundantly available (AA). *Puntius chola*, *Barbodes sarana* and *Securicula gora* were moderately available (MA). While the abundance of *Salmostoma acinaces* and *Osteobra-*

Table 1. Top ten fish species (abundance) of the Bamui *beel*

Serial number (chronologically)	Species
01	<i>Puntius ticto</i>
02	<i>Channa punctata</i>
03	<i>Labeo rohita</i>
04	<i>Catla catla</i>
05	<i>Cyprinus carpio</i>
06	<i>Ctenopharyngodon idella</i>
07	<i>Heteropneustes fossilis</i>
08	<i>Mystus vittatus</i>
09	<i>Wallago attu</i>
10	<i>Mystus bleekeri</i>

ma cotio was common and rare, respectively. Biodiversity research using catch observation surveys in this experiment was demonstrated that many species of Snakehead, Perch, and Eels were available in the Bamui *beel*. Seven species of Perch were identified in Bamui *beel* throughout the study. *Chanda lala*, *Chanda nama* and *Anabas testudineus* were moderately available (MA) among them. According to local fishermen, the rest of them were commonly available (CA) (Table 2). Four snakehead species were identified in this study period. *Channa punctata* and *Channa orientalis* were commonly available (CA). In addition to this, *Channa striata* was moderately available (MA), whereas *Channa marulius* was rarely available. Various Eels species such as *Macrognathus aral* and *Mastacembelus armatus* were moderately available (MA), but *Mastacembelus pancalus* and *Monopterusuchia* were rarely available (RA). Two kinds of Loaches were found in Bamui *beel* throughout the research period and both were commonly available (CA). Moreover, Clupeids were identified in which Indian River Shad was rarely available and the Ganges River Sprat was commonly available. Because there was no prior experiment on fish biodiversity and abundance of Bamui *beel*, it was not possible to analyze the development in diversification of the *beel* by comparing with earlier ones. Species compositions (%), productivity (kg/ha) and production (MT) of different species groups was observed in Table 3. The highest composition, productivity and production was found for Small Indigenous Species (SIS) with the value of 63.4%, 256.25 kg/ha and 3.672 MT, respectively. The diversity and abundance of aquatic organisms in the Bamui *beel*, however, was comparable to that of several wetlands and *beel* ecosystems [32]. However, the current study could be a useful starting point for any future assessments of fish diversity of Bamui *beel*.

However, two feather-back species were observed in all the catches. Finally, only species of prawn (*Solenocera crassicornis*) found in this *beel*, and it was critically endangered (Table 2). Several important species of the *beel* have been highlighted in this experiment (Fig. 4). The Pilati *beel* hosted a total of 55 fish species, among them most dominant order was cypriniformes (38.18%) mirroring the findings of present study [33]. The presence of 16 fish species from

the Cyprinidae family in the Dogger *beel* was documented which was similar to our current study [34].

In terms of group abundance, Barbs and Minnows was dominated (19.56%) followed by Catfishes (17.38%), Carps (15.22%), Perches (15.22%), Snakeheads (8.70%), Eels (8.70%), Loaches (4.35%), Clupeids (4.35%), Feather-backs (4.35%) and Prawns (2.17%) (Fig. 5). In Figure 6, Cypriniformes (39.12%) was the most dominating order followed by Siluriformes (17.40%), Perciformes (17.40%), Synbranchioformes (8.68%), Anabantiformes (6.51%), Clupeiformes (4.35%), Osteoglossiformes (4.35%) and Decapoda (2.18%). Moreover, the highest amount of fishes was under the family Cyprinidae (34.76%) followed by Channidae (8.68%), Bagridae (6.51%), Mastacembelidae (6.51%), Siluridae (4.35%), Cobitidae (4.35%), Ambassidae (4.35%), Osphronemidae (4.35%), Clupeidae (4.35%), Nymphalidae (2.18%), Claridae (2.18%), Heteropneustidae (2.18%), Nandidae (2.18%), Anabantidae (2.18%), Synbranchidae (2.18%), and Soleceridae (2.18%) showing in Figure 6. Study on *beel* fisheries in Bangladesh is very few, assessment of fish biodiversity in Basuakhali *beel* at Khulna district was recorded [35]. Likewise this experiment, cypriniforms order was recorded as the most dominant with 12 species in Gorai River [36]. Also fish biodiversity research on various location of Bangladesh reported presence of similar fish species but varying numbers, for example, a total 57 species of fish from the Old Brahmaputra river [37], 106 species of fish which belongs to 31 families in Chalan *beel* [38], 92 species of fish from Sylhet-Mymensingh sub-basins [39].

Although the Bamui *beel* is the habitat of an extensive array of aquatic organisms, there are significant issues about the existence and survival of aquatic diversification because of an assortment of human and ecological phenomena that are lowering richness in the *beel* region. Various biodiversity based fish research is going to make a clear concept on fish species existence. The Cyprinidae family contained the most fish species which was about 54 species in Charar *beel* [40]. Cyprinidae family contributed 17 species, which made it the most abundant family in the Bhawal *beel* [41]. Jat punti (*Puntius sophore*) has been reported as the most available and dominant species at the Hatil *beel* of Bangladesh [42]. Availability of low sediment and pure water in Bamui *beel* made it a suitable place for fish to reproduce. As per report, over half of the total fish population (53.36%) in Bangladesh fell under the "Least Concern (LC)" category [43]. Additionally, around 14.55% and 10.90% of the overall fish species were classified as near-threatened and vulnerable in the same study, respectively. Natural vegetation offers a natural biological balance for sheltering other broodfish, while emergent and submerged vegetation is an excellent home for small and medium-sized fishes. Similar research was conducted on many rivers of Bangladesh such as the Tista River [25], the Padma River [44], the Mahananda river [45] and the Choto Jamuna River [42].

All fish species in Bamui *beel* were negatively impacted by scorching *beels*, high precipitation, over exploitation, land subsidence, usage of hazardous gears to catch fishes, tem-

Table 2. List of freshwater species with their availability and conservation status found in Bamui beel during experiment

Order	Family	Scientific name	English name	Common name	Present status	Conservation status	
						BD	Global
Cypriniformes	Cyprinidae	<i>Labeo rohita</i> (Hamilton, 1822)	Rohu	Rui	MA	LC	LC
		<i>Cirrhinus reba</i> (Hamilton, 1822)	Reba Carp	Lachu	CR	NT	LC
		<i>Labeo calbasu</i> (Hamilton, 1822)	Orange Fin Labeo	Kalbasu	MA	LC	LC
		<i>Cyprinus carpio</i> (Hamilton, 1822)	Common Carp	Carpio	MA	NT	VU
		<i>Ctenopharyngodon idella</i> (Hamilton, 1822)	Ray-Finned Fishes	Grass Carp	MA	NT	NE
		<i>Labeo gonius</i> (Hamilton, 1822)	Kuria Labeo	Gonia	MA	NT	LC
		<i>Esomus danricus</i> (Hamilton, 1822)	Stripped Flying Barb	Darkina	CR	DD	NE
		<i>Puntius ticto</i> (Hamilton, 1822)	Ticto Barb	Tit Punti	AA	VU	LC
		<i>Puntius sophore</i> (Hamilton, 1822)	Spotfin Swamp Barb	Jat Punti	AA	LC	LC
		<i>Puntius guganio</i> (Hamilton, 1822)	Glass Barb	Mola Punti	AA	LC	LC
		<i>Puntius chola</i> (Hamilton, 1822)	Chola Barb	Chola Punti	MA	LC	LC
		<i>Amblypharyngodon mola</i> (Hamilton, 1822)	Mola Carplet	Mola	AA	LC	LC
		<i>Osteobrama cotio</i> (Hamilton, 1822)	Cotio	Dhela	RA	NT	LC
		<i>Securicula gora</i> (Hamilton, 1822)	Chela Gora	Ghora Chela	MA	NT	LC
		<i>Salmostoma acinaces</i> (Valenciennes, 1844)	Silver Razorbelly Minnow	Chela	CR	DD	LC
		<i>Barbodes sarana</i> (Hamilton, 1822)	Olive Barb	Shorputi	MA	NT	LC
		<i>Lepidocephalus guntea</i> (Hamilton, 1822)	Guntea Loach	Gutum	CR	LC	LC
Siluriformes	Cobitidae	<i>Botia dario</i> (Hamilton, 1822)	Bengal Loach	Bou Rani	CR	EN	LC
		<i>Wallago attu</i> (Linnaeus, 1758)	Freshwater Shark	Boal	CR	VU	VU
		<i>Ompok pabo</i> (Hamilton, 1822)	Pabo Catfish	Pabda	CR	CR	NT
		<i>Clarias batrachus</i> (Hamilton, 1822)	Walking Catfish	Magur	MA	LC	LC
		<i>Heteropneustes fossilis</i> (Bloch & Schneider, 1801)	Asian Stingray Catfish	Shing	CR	LC	LC
		<i>Pseudotropius atherinoides</i> (Bloch, 1794)	Indian Potasi	Batashi	AA	LC	NE
		<i>Sperata aor</i> (Hamilton, 1822)	Long-Whiskered Catfish	Air	CR	VU	LC
		<i>Mystus bleekeri</i> (Day, 1877)	Bleeker's Mystus	Gulsha Tengra	AA	LC	LC
		<i>Mystus vittatus</i> (Hamilton, 1822)	Asian Striped Catfish	Tengra	AA	LC	LC
		<i>Chanda lala</i> (Hamilton, 1822)	Highfin Glassy Perchlet	Lal Chanda	MA	LC	NE
Perciformes	Ambassidae	<i>Chanda nama</i> (Hamilton, 1822)	Elongate Glass Perchlet	Lamba Chanda	MA	LC	LC
		<i>Chanda beculis</i> (Hamilton, 1822)	Dewelled Nawab	Chanda	CR	EN	NE

Table 2 (cont). List of freshwater species with their availability and conservation status found in Bamui beel during experiment

Order	Family	Scientific name	English name	Common name	Present status	Conservation status	
						BD	Global
Anabantiformes	Nandidae	<i>Nandus nandus</i> (Hamilton, 1822)	Gangetic Leaf Fish	Meni	CR	NT	LC
	Channidae	<i>Channa marulius</i> (Hamilton, 1822)	Giant Snakehead	Gozar	RA	EN	LC
		<i>Channa striata</i> (Bloch, 1793)	SNAKEHEAD Murrel	Shol	MA	LC	LC
		<i>Channa punctate</i> (Bloch, 1793)	Spotted Snakehead	Taki	CR	LC	LC
		<i>Channa orientalis</i> (Bloch & Schneider, 1801)	Asiatic Snakehead	Cheng	CR	LC	LC
		<i>Anabas testudineus</i> (Bloch, 1793)	Climbing Perch	Koi	MA	LC	LC
Synbranchiformes	Anabantidae	<i>Trichogaster fasciata</i> (Bloch & Schneider, 1801)	Banded Gourami	Baro Kholisha	CR	LC	LC
	Osphronemidae	<i>Trichogaster lalius</i> (Hamilton, 1822)	Red Gourami	Lal Kholisha	CR	LC	LC
		<i>Macragnathus aral</i> (Bloch & Schneider, 1801)	One-Stripe Spiny Eel	Tara Baim	MA	DD	LC
		<i>Mastacembelus pancalus</i> (Hamilton, 1822)	Striped Spiny Eel	Guchi Baim	RA	LC	LC
		<i>Mastacembelus armatus</i> (Lecepede, 1800)	Tire-Track Spinyeel	Baim	MA	EN	NE
		<i>Monopterusuchia</i> (Hamilton, 1822)	Gangetic Mudde	Kuchia	RA	VU	VU
Clupeiformes	Synbranchidae	<i>Gudusia chapra</i> (Hamilton, 1822)	Indian River Shad	Chapila	RA	VU	LC
	Clupeidae	<i>Corica soborna</i> (Hamilton, 1822)	The Ganges River Sprat	Kachki	CR	LC	LC
Osteoglossiformes	Notopteridae	<i>Notopterus notopterus</i> (Pallas,1769)	Bronze Featherback	Foli	MA	VU	LC
		<i>Chitala chitala</i> (Hamilton, 1822)	Humped Featherback	Chitol	MA	EN	NT
Decapoda	Soleniceridae	<i>Solenocera crassicornis</i> (H. Milne Edwards,1837)	Red Prawn	Gura Chingri	CR	LC	NE

NE: Not Evaluated; DD: Data deficient; LC: Least concern; NT: Near threatened; VU: Vulnerable; EN: Endangered; RA: Rarely available; MA: Moderately available; CR: Critically endangered; BD: Bangladesh.

Table 3. Species compositions (%), productivity (kg/ha) and production (MT) of different groups observed in the *beel*

Group name	Species compositions (%)	Productivity (kg/ha)	Total production in the beel (MT)
Small indigenous species	63.4	256.25	3.672
Large indigenous group	21.67	146.77	1.876
Exotic fishes	13.26	94.63	1.232
Prawn	1.61	17.48	0.243
Total	100		7.023

Table 4. Causes of diversity degradation mentioned by local ordinary people, fishermen and landowners (n=357)

Causes of affecting species diversity	No. of respondents (%)
Drying beel each year	91.67
Excessive fish catch	90.45
Usage of harmful fishing equipment	88.72
Extensive agricultural practices	72.26
Building lane and elevation near the beel	66.32
Usage of insecticides	61.48
Soil erosion	56.15
Building a blockade	44.42
Government negligence	30.64
Draught	23.71

perature inversions, and the addition of inorganic supplement to capture fishes. Every year, those who rent the *beel*, dewater the entire water body (generally using a powerful pump) before subletting them to the other groups, who also repeat the same scenario once again since some water is left in the *beels* just after primary dehydration. Identical issues were discovered which were engaged to involve biodiversity degradation. The main reasons behind the reduction in the biodiversity of Bamui *beel* are mainly drying *beel* every year (91.67%), overfishing (90.45%), usage of harmful fishing equipment (88.72%), and extensive agricultural practices (72.26%), building lane and elevation near the *beel* (66.32%), usage of insecticides (61.48%), soil erosion (56.15%), building a blockade (44.42%), government negligence (30.64%), draught (23.71%) (Table 4).

Biodiversity Index Status

Biodiversity index of the Bamui *beel* during different seasons (post-monsoon, monsoon and pre-monsoon) are shown in Figure 7. The highest Evenness score of 0.247 during pre-monsoon was suggested a relatively balanced distribution of species abundance. This could mean that no single species was dominating the ecosystem, and various species coexist in similar numbers. In contrast, the lower Evenness score of 0.213 during the monsoon implied a more uneven distribution, with some species possibly becoming more dominant. The range of values between 1.992 and 2.114 indicated a moderate level of diversity in Bamui *beel*. A higher index generally suggests a more diverse ecosystem [5]. The slight variation across

seasons could signify changes in the composition or abundance of species, contributing to the overall diversity. The maximum Simpson's dominance index of 0.883 in pre-monsoon was suggested a relatively high dominance of certain species during that period. As the dominance decreased to a minimum of 0.852 in the monsoon, it implied a reduction in the influence of dominant species, leading to a more evenly distributed community. Similar pattern of Simpson's dominance index (0.325 in monsoon and 0.893 in pre-monsoon) was observed in Bangladesh's Dhaleshwari River [46]. Shannon Weaver diversity index (H') considered both the number of species and the distribution of individuals among species of the Bamui *beel*. For observational data, the Shannon-Weaver diversity index (H') normally varied from 1.5 to 3.5, it seldom exceeded 4.0 and could rise over 5.0 only when samples contained one million organisms [47]. The value of Shannon-Weaver diversity index (H') was the highest in pre-monsoon (2.114), whereas the value was the lowest in monsoon (1.992). Similarly, Shannon-Weaver diversity index (H') also demonstrated that the higher availability of species in pre-monsoon compared to monsoon and post-monsoon. Analogous result ranging from 0.95 to 2.62 for the Shannon-Weaver diversity index (H') was also observed in the Bakkhali River estuary [48]. Pielou's evenness index (J') in Bamui *beel* was the highest during pre-monsoon (0.247) and the lowest during monsoon (0.213). The Richness index in Hakaluki Haor was exhibited a range between 3.889 (in November) and 8.679 (in January) [49]. Correspondingly, Pielou's evenness index (J') values varied from 0.4879 (in September) to 0.8252 (in May), while Simpson's dominance index values spanned from 0.625 (in September) to 0.9423 (in May). The Shannon-Weaver diversity index (H') was showed fluctuations from 1.726 (in November) to 3.406 (in May) [49]. In the Shari Goyain river, Simpson's dominance index (D) was ranged from 3.430 (in December) to 2.325 (in March) and Pielou's evenness index (J') values was ranged from 0.508 (in November) to 0.561 (in March) [50].

Stakeholder's Perception on Bamui Beel Fisheries

Regarding fishery productivity and ecology, each factor had favorable and unfavorable effects. 357 people involving fish related work (property owners, fishers, and ordinary people) took part in the questionnaire and provided their meaningful thoughts on their meaningful thoughts and experience on Bamui *beel* fisheries (Fig. 8). The main question was *beel* fisheries should be permitted 62.36% of

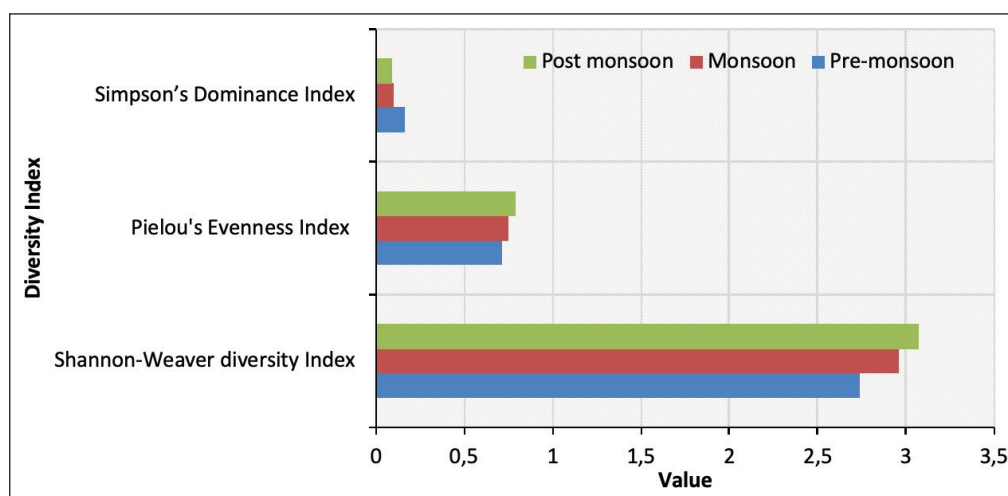


Figure 7. Biodiversity index of Bamui *beel* during three seasons (post-monsoon, monsoon and pre-monsoon).

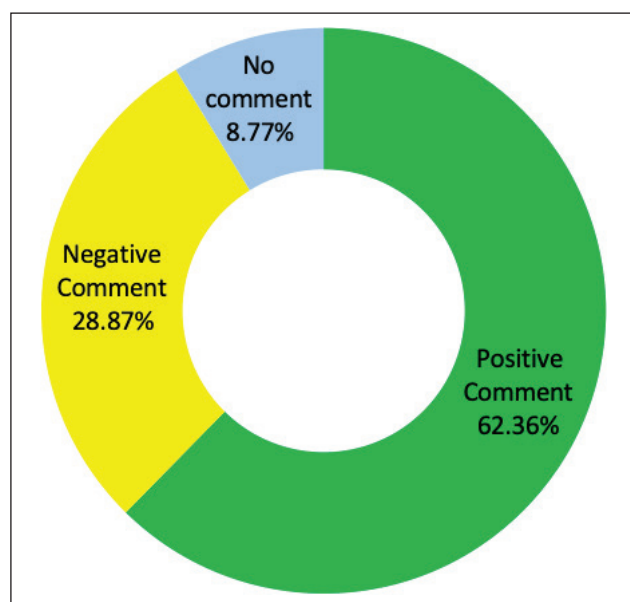


Figure 8. Stakeholder's (n=357) opinion from the study area.

total participants agreed about permitting the *beel* fisheries, while negative feedback was given by 28.87%, and 8.77% was not sure or didn't share their opinion (Fig. 8). All negatively participants responded that they didn't have total access to harvest fishes in the *beel* region during the whole year. Once questioned that there was a potentiality of effective fish reproduction (specially the threatened species) to keep the sustainable balance for the future generation, all the respondents replied affirmatively. Additionally, the respondents also expressed that dewatering the water bodies was degrading the habitat of fishes. Statement given above, inferred that fish production would increase the productivity and thus could maintain a sustainable biodiversity in the Bamui *beel*.

In essence, the initial biodiversity and conservation assessment of Bamui *Beel* not only contributes to our scientific understanding of this unique ecosystem but also provides a foundation for concrete conservation actions. By recog-

nizing its importance and addressing the threats it faces, we can work towards ensuring the long-term health and resilience of the Bamui *beel* for future generations.

CONCLUSION

In assumption, the inaugural biodiversity and conservation assessment of the Bamui *beel* in Bangladesh has provided valuable insights into the current status and approaching threats facing this ecosystem. About 46 fish species were found that was under the 18 taxonomical families and 8 orders, within these species 37% were commonly available and 11% were abundantly available in terms of biodiversity status. The comprehensive examination of biodiversity has unveiled a nuanced understanding of the ecological dynamics, with a particular focus on the diverse array of species inhabiting the Bamui *beel*. The identification of threats serves as a crucial foundation for informed conservation efforts. The findings of the study were underscored that the urgency of implementing strategic conservation measures to mitigate the identified threats and preserve the biodiversity of the Bamui *beel*.

ACKNOWLEDGEMENTS

The authors would like to express sincere gratitude to the respectable Dean of the Faculty of Fisheries at Sylhet Agricultural University for providing all kinds of essential facilities and support to conduct the present study.

DATA AVAILABILITY STATEMENT

The author confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

In the present study, fish were handled according to the guidelines as described the Animal Ethics Committee of Sylhet Agricultural University (Memo: SAU/AEC/FOF/ARM-102).

FUNDING STATEMENT

The first author warmly acknowledges the financial support received from the National Science and Technology (NST) Fellowship for his MS research work.

REFERENCES

- [1] M. Y. Hossain, "Length-weight, length-length relationships and condition factor of three Schibid catfishes from the Padma River North western Bangladesh," *Asian Fisheries Science*, Vol. 23, pp. 329–339, 2010a. [\[CrossRef\]](#)
- [2] M. Y. Hossain, "Morphometric relationships of length-weight and length-length of four Cyprinid small indigenous fish species from the Padma River (NW Bangladesh)," *Turkish Journal of Fisheries and Aquatic Sciences*, Vol. 10, pp. 131–134, 2010b.
- [3] B. C. Majumdar, "Comparison of the changes in nutritional quality of three important small indigenous fish species in Bangladesh at room temperature (27–31°C): A review," *Journal of Animal Research and Nutrition*, Vol. 2, Article 15, 2017. [\[CrossRef\]](#)
- [4] S. Hemal, M. S. Uddin, M. S. Uddin, B. C. Majumdar, M. G. Rasul, and M. T. Alam, "Present status and problems of fish seed marketing in Sylhet district, Bangladesh," *Research in Agriculture, Livestock and Fisheries*, Vol. 4, pp. 45–54, 2017. [\[CrossRef\]](#)
- [5] B. C. Majumdar, S. I. Paul, M. Hasan, T. Kabir, M. Islam, and I. E. Kabir, "Fish biodiversity assemblages and fishing gears used at Chinadi Beel in Narsingdi District of Bangladesh," *International Journal of Agriculture, Environment and Biotechnology*, Vol. 13, pp. 403–413, 2020. [\[CrossRef\]](#)
- [6] S. I. Paul, B. C. Majumdar, M. Hasan, A. K. Sarker, A. Baidya, and M. Hakim, "Fish Biodiversity, Threat Status and Conservation Significance of the Jamuna River, Bangladesh," *Croatian Journal of Fisheries*, Vol. 79, pp. 173–186, 2021. [\[CrossRef\]](#)
- [7] H. Sheikh, A. R. Mondal, B. C. Majumdar, A. Rayhan, and M. N. Hossen, "Spawning and mortality of eggs and larvae produced by different brood sizes of Walking Catfish (*Clarias batrachus* L.)," *Journal of Applied and Advanced Research*, Vol. 3, pp. 78–83, 2018. [\[CrossRef\]](#)
- [8] FAO, "The State of World Fisheries and Aquaculture 2020. Sustainability in action. Rome," 2020.
- [9] B. C. Majumdar, D. C. Shaha, M. G. Rasul, and M. Khan, "Fish Production in Floodplain of Bangladesh: A Review," *International Journal of Natural Science*, Vol. 6, pp. 89–95, 2016.
- [10] B. C. Majumdar, and I. Rashid, "Microbiological properties of dry salted Hilsa, *Tenualosa ilisha* (Hamilton, 1822) fish of Bangladesh," *Journal of Fisheries and Life Sciences*, Vol. 2, pp. 4–9, 2017.
- [11] M. N. H. Shovon, B. C. Majumdar, and Z. Rahman, "Heavy metals (lead, cadmium and nickel) concentration in different organs of three commonly consumed fishes in Bangladesh," *Fisheries and Aquaculture Journal*, Vol. 8, Article 207, 2017.
- [12] IUCN, "Introduction to Community Based Haor and Floodplain Resource Management. IUCN Bangladesh Country Office, Dhaka, Bangladesh," Article 42, 2004.
- [13] B. Chakraborty, S.N. Labh, R. Rani, and S. Bhattacharjee, "Biodiversity and Management Status of Chharia beel in Northern Bangladesh," *Journal of Scientific Research in Medical and Biological Sciences*, Vol. 2, pp. 63–80, 2021a. [\[CrossRef\]](#)
- [14] M. A. Crains, and R. T. Lackey, "Biodiversity and management of natural resources: the issues," *Fisheries*, Vol. 17, pp. 6–10, 1992. [\[CrossRef\]](#)
- [15] M. M. Shamsuzzaman, M. M. Islam, N. J. Tania, M. A. Al-Mamun, P. P. Barman, and X. Xu, "Fisheries resources of Bangladesh: Present status and future direction," *Aquaculture and Fisheries*, Vol. 2, pp. 145–156, 2017. [\[CrossRef\]](#)
- [16] Banglapedia, "National Encyclopedia of Bangladesh, Asiatic Society of Bangladesh," 1st edn., February, Dhaka, Bangladesh, 2004.
- [17] K. K. U. Ahmed, S. U. Ahamed, K. R. Hasan and M. G. Mustafa, "Option for formulating community-based fish sanctuary and its management in beel ecosystem in Brahmanbaria," *Bangladesh Journal of Fisheries*, Vol. 30, pp. 1–10, 2007.
- [18] B. K. Chakraborty, S. Bhattacharjee, and S. Muniya, "A Study of aquatic biodiversity of Shuthi-Shaiduli river of Bangladesh," *International Journal of Biological Innovations*, Vol. 3, pp. 58–67, 2021b. [\[CrossRef\]](#)
- [19] B. K. Chakraborty, M. H. Shahroz, A. B. Bhuiyan, S. Bhattacharjee, and S. Chatteraj, "Status of Indian major carp's spawns in the Halda River along with marketing and economic condition of the Fishers and related collectors," *International Journal of Biological Innovations*, Vol. 1, pp. 40–50, 2019. [\[CrossRef\]](#)
- [20] B. K. Chakraborty, M. J. A. Mirza, "Study of aquatic biodiversity of Gharia beel of Bangladesh," *Journal of Crop and Weed*, Vol. 3, pp. 23–34, 2007.
- [21] M. J. O'Connell, "Detecting, measuring and reversing changes to wetlands," *Wetlands Ecology and Management*, Vol. 11, pp. 397–401, 2003. [\[CrossRef\]](#)
- [22] F. Danielsen, D. S. Balet, M. K. Poulsen, M. Enghoff, C. M. Nozawa, and A. E. Jensen, "A system for monitoring biodiversity in protected areas of a developing country," *Biodiversity & Conservation*, Vol. 9, pp. 1671–1705, 2000.
- [23] M. A. Sultana, S. K. Mazumder, and M. Kunda, "Diversity of fish fauna and fishing gears used in the River Banar, Mymensingh, Bangladesh," *Bangladesh*

- Journal of fisheries, Vol. 30, pp. 229–240, 2018.
- [24] M. Shah, N. Chowdhury, M. S. Hossain, N. G. Das, and P. Barua, “Environmental variables and fisheries diversity of the Naaf River Estuary, Bangladesh,” *Journal of Coastal Conservation*, Vol. 15, pp. 163–180, 2011. [\[CrossRef\]](#)
- [25] M. R. Khan, M. I. Miah, M. B. Hossain, A. Begum, M. H. Minar, and R. Karim, “Fish biodiversity and livelihood status of fishing community of Tista River, Bangladesh,” *Global Veterinaria*, Vol. 10, pp. 417–423, 2013.
- [26] M. A. Hossain, M. Nahiduzzaman, M. A. Sayeed, M. E. Azim, M. A. Wahab, and P. G. Olin, “The Chalan beel in Bangladesh: Habitat and biodiversity degradation, and implications for future management,” *Lakes & Reservoirs: Research & Management*, Vol. 14, pp. 3–19, 2009. [\[CrossRef\]](#)
- [27] M. A. Ehshan, M. S. Hossain, A. Razzaque, and M. S. Alam, “Kua-an unusual but important fishery of Chanda beel,” *Bangladesh Journal of Zoology*, Vol. 28, pp. 69–74, 2000.
- [28] M. A. H. M. Kamal, M. A. Kawsar, D. Pandit, M. Kunda, K. Tabassum, and M. T. Alam, “Fish biodiversity at Kawadighi Haor of northeastern Bangladesh: addressing fish diversity, production and conservation status,” *Aquatic Sciences and Engineering*, Vol. 37, pp. 151–160, 2022.
- [29] K. R. Clarke, R. N. Gorley, P. J. Somerfield, and R. M. Warwick, “Change in marine communities: an approach to statistical analysis and interpretation (PRIMER-E),” *Plymouth Marine Laboratory*, Plymouth, UK, 2014.
- [30] C. Vijaylaxmi, M. Rajshekhar, K. Vijaykumar, “Freshwater fishes distribution and diversity status of Mullameri river, a minor tributary of Bheema river of Gulbarga district, Kamataka,” *International Journal of Systems Biology*, Vol. 2, pp. 1–9, 2010.
- [31] T. M. DeJong, “A comparison of three diversity indices based on their components of richness and evenness,” *Oikos*, pp. 222–227, 1975. [\[CrossRef\]](#)
- [32] M. R. Talukder, M. A. Hussain, M. Kunda, A. H. A. Rashid, D. Pandit, and T. A. Sumon, “Checklist of fish species in the Shari-Goyain River, Bangladesh: Threats and conservation measures,” *Indian Journal of Geo Marine Sciences*, Vol. 50, pp. 148–155, 2021. [\[CrossRef\]](#)
- [33] J. Ferdous, A. Sultana, S. J. Mitu, A. R. Shrabon, Z. Rahman, and R. Mia, “Current status and threats to fish biodiversity of Pailati beel, Bangladesh,” *Biodiversity Studies*, Vol. 2, pp. 37–47, 2023. [\[CrossRef\]](#)
- [34] M. A. Siddiq, M. I. Miah, Z. F. Ahmed, and M. Asadujjaman, “Present status of fish, fishers and fisheries of Dogger Beel in Hajigonj Upazila, Chandpur, Bangladesh,” *Journal of Aquatic Science*, Vol. 1, pp. 39–45, 2013.
- [35] M. A. Rahman, A. Khamari, B. Mandal, M. R. Ullah, M. B. Hossen, M. A. Alam and N. Saha, “Assessment of Fish Biodiversity in Basuakhali Beel under Tero-khada Upazilla, Khulna, Bangladesh,” *Asian Journal of Research in Biosciences*, Vol. 1, pp. 55–64, 2019.
- [36] M. A. Hanif, M. A. B. Siddik, A. Nahar, M. R. Chaklader, R. J. Rumpa, M. J. Alam, and S. Mahmud, “The current status of small indigenous fish species (SIS) of River Gorai, a distributary of the river Ganges, Bangladesh,” *Journal of Biodiversity & Endangered Species*, Vol. 4, Article 162, 2016. [\[CrossRef\]](#)
- [37] M. M. Ali, M. B. Hossain, M. A. Rahman, A. Habib, “Diversity of fish fauna in the Chitra river of Southwestern Bangladesh: present status, threats and recommendations for conservation,” *Asian Journal of Applied Sciences*, Vol. 7, pp. 635–643, 2014. [\[CrossRef\]](#)
- [38] M. A. Sayeed, “Fish biodiversity in the Chalan Beel a natural depression in North West Bangladesh,” PhD Thesis, Department of Fisheries Biology and Genetics, Bangladesh Agricultural University, Mymensingh, Article 64, 2010.
- [39] K. Y. Haroon, G. C. Halder, S. C. Rahman, M. A. Razzaque, M. Alam, and N. S. M. Amin, “Sylhet Mymensingh Basin Fish Stock Assignment,” *Bangladesh Fisheries Research Institute (BFRI), Riverine Station, Chandpur, Bangladesh*, Article 81, 2002.
- [40] N. A. Raushon, M. G. S. Riar, M. H. Rahman, M. Al-Mazed, and S. K. Paul, “Aquatic Biodiversity of Charar Beel Gabtoli, Bogura,” *Journal of the Bangladesh Society for Agricultural Science and Technology*, Vol. 16, pp. 133–138, 2019.
- [41] M. A. Sultana, M. Kunda, and S. K. Mazumder, “Status and decline cause of fish diversity of Bhawal beel, Bangladesh,” *Malaysian Journal of Medical and Biological Research*, Vol. 6, pp. 93–100, 2019. [\[CrossRef\]](#)
- [42] S. M. Galib, S. M. A. Naser, and A. B. M. Mohsin, “Fish biodiversity of river Choto Jamuna, Bangladesh: Present status and conservation needs,” *International Journal of Biodiversity and Conservation*, Vol. 5, pp. 389–395, 2013.
- [43] IUCN, “The international union for conservation of nature’s red list of threatened species,” *IUCN Bangladesh Country Office, Dhaka, Bangladesh*, Article 71, 2017.
- [44] M. M. Rahman, M. Y. Hossain, F. Ahamed, S. B. Fatematuzzhura, E. M. Abdallah, and J. Ohtomi, “Biodiversity in the Padma distributary of the Ganges River, northwestern Bangladesh: Recommendations for conservation,” *World Journal of Zoology*, Vol. 7, pp. 328–337, 2012.
- [45] B. M. Mohsin, and H. Emdadul, “Diversity of fishes of Mahananda River at Chapai Nawabgonj district,” *Research Journal of Biological Sciences*, Vol. 4, pp. 828–831, 2009.
- [46] M. Islam, and R. Yasmin, “Assemblage, abundance and diversity of fish species in River Dhaleshwari, Bangladesh,” *Asian Journal of Fisheries and Aquatic Research*, Vol. 2, pp. 1–28, 2018. [\[CrossRef\]](#)
- [47] M. A. Hanif, M. A. B. Siddik, M. R. Chaklader, S. Mahmud, A. Nahar, M. S. Hoque, and S. Munilku-

- mar, “Biodiversity and conservation of threatened freshwater fishes in Sandha River, South West Bangladesh,” *World Applied Sciences Journal*, Vol. 33, pp. 1497–1510, 2015.
- [48] M. Rashed-Un-Nabi, M. A. Al-Mamun, M. H. Ullah, and M. G. Mustafa, “Temporal and spatial distribution of fish and shrimp assemblage in the Bakkhali river estuary of Bangladesh in relation to some water quality parameters,” *Marine Biology Research*, Vol. 7, pp. 436–452, 2011. [\[CrossRef\]](#)
- [49] M. M. Iqbal, S. Nasren, M. A. A. Mamun, and M. M. Hossain, “Fish assemblage including threatened species in Hakaluki Haor, Sylhet, Bangladesh,” *Journal of Agriculture in the Topics*, Vol. 30, pp. 233–246, 2015.
- [50] S. R. Das, D. Pandit, A. Harun-Al-Rashid, N. Tasnim, and M. Kunda, “Impacts of brush pile fishing on fish biodiversity: A case study of the Shari-Goyain River in Bangladesh,” *Heliyon*, Vol. 8, Article e09903, 2022. [\[CrossRef\]](#)



Research Article

Evaluation of the environmental exposure risks of pesticides used in vegetable production in Türkiye

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ARTICLE INFO

Article history

Received: 04 August 2023

Accepted: 10 December 2023

Key words:

DynamiCROP; Environmental partitioning; Equilibrium-criterion model; Multi-media environmental modeling; Tomato; Pesticide residue

ABSTRACT

In this study, first, a list of pesticides that can potentially pose environmental exposure risks was compiled by analyzing the recent literature on residue levels in fresh vegetables produced in Türkiye. Then, by using the fundamental environmental partitioning properties of these pesticides, their potential multi-media environmental distributions were assessed. Acetamiprid, chlorpyrifos, and pyridaben were among the pesticides that frequently exceeded the residual limit values. Multi-media environmental modeling was conducted for these three pesticides using an evaluative four-compartment (air, soil, water, sediment) model. Compartmental distributions, inter-compartmental mass transfer rates, advective, and reactive losses were estimated for the selected pesticides after their simulated application to soil. The ranking of overall persistence among the pesticides was found to be pyridaben > chlorpyrifos > acetamiprid. The percentage mass distribution of acetamiprid in water was higher due to its low volatility and high solubility. The overall persistence of chlorpyrifos was limited by its higher partitioning to air although it is more persistent than pyridaben in other compartments. To investigate the residue dynamics of the three pesticides in tomato crops, temporal changes in harvest fractions were compared using the regression equations of the crop model dynamiCROP. Acetamiprid was estimated to be taken up at higher rates in tomatoes after initial application. The residue dynamics of chlorpyrifos and pyridaben were found to be similar. The quantitative methods in this study can be used to assess the environmental risks associated with commonly used pesticides in Türkiye and to address the issue of exceeding residue limits in agricultural products.

Cite this article as: Kula EP, Göktaş RK. Evaluation of the environmental exposure risks of pesticides used in vegetable production in Türkiye. Environ Res Tec 2024;7(1)83–96.

INTRODUCTION

Türkiye is one of the leading countries in the global vegetable production. According to the data from the Food and Agriculture Organization of the United Nations (FAO), in 2021, Türkiye ranked fourth in total fresh vegetable production, following China, India, and the United States [1]. Regarding tomatoes, which are among the most widely produced vegetables globally, Türkiye holds the position of the third-largest producer,

following China and India. Examining the FAO's data on total vegetable exports for the year 2021, Türkiye ranks eighth in terms of export quantity (2.34 million tons) and twelfth in terms of export value (\$1.9 billion) [2]. The vegetable product that Türkiye exported the most in 2021 was tomatoes, with an export quantity of approximately 606,583 tons and a value of around \$357 million. By enhancing agricultural production efficiency and product quality, Türkiye has the potential to obtain a larger share in global agricultural trade.

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Globally, agricultural areas experience approximately a 35% loss due to diseases, pests, and weeds [3]. Plant protection processes need to be an essential part of agricultural production. The fundamental principle is to protect agricultural crops from diseases, agricultural pests, and weed infestations without causing harm to the natural environment. Pesticides are used in agriculture to prevent agricultural losses, achieve high yields, and meet the increasing demand. According to the study conducted by Doğan and Karpuzcu [4], pesticide use in Türkiye is approximately 1.66 kg/ha, which is not significantly higher compared to countries with similar magnitude of land areas devoted to agricultural production. However, pesticide use in Türkiye is concentrated in the Mediterranean Region, where agricultural activities are intensively conducted [5].

Pesticide use in agriculture has the advantage of increasing productivity and production quantity. However, the environmental pollution caused by pesticides and the presence of pesticide residues in agricultural products have negative implications in terms of health and economics. The European Union utilizes the Rapid Alert System for Food and Feed (RASFF) portal to monitor all food and animal feed products imported from non-EU countries, including animal feed, animal-derived products, milk and dairy products, honey, plant-based products, and medicinal plants. Türkiye is the country with the highest number of notifications compared to other countries exporting to the EU [6]. According to the 2020 report published by the RASFF portal, there were 405 notifications indicating that pesticide residue values in products imported from Türkiye exceeded the maximum residue level (MRL) [7]. Notifications regarding pesticide residues can be queried in real-time through the RASFF Window website [8].

Numerous studies have been conducted in Türkiye investigating the residue levels of pesticides in agricultural products. A review study conducted by Tiryaki [9] compiled the results of pesticide residue analyses in fresh and/or dried fruits and vegetables, as well as processed agricultural products in Türkiye. In the study by Tözün and Akar [10], 35 studies conducted after 2010, analyzing pesticide residues in food items were examined. It was reported that the maximum residue level (MRL) was exceeded in approximately half of the food samples.

The adverse effects of all harmful chemicals, including pesticides, on humans can vary depending on the level and duration of exposure, and also, on the toxic effects of the chemical. Human exposure to pesticides can occur during their production, storage, transportation, and use, and via consumption of products containing chemical residues. Pesticides can enter the human body through inhalation, skin contact, and gastrointestinal pathways [11]. Pesticide exposure in humans can result in acute effects such as respiratory problems, headaches, skin issues, and nausea, while long-term effects such as neurotoxicity, endocrine disruption, and cancer have also been observed [12].

After application, pesticides can transport to environmental media beyond the intended agricultural target. The fate

and transport of the pesticide, once released into the environment, depend on the chemical and environmental characteristics in addition to the application rate. Pesticides can contribute to atmospheric pollution through volatilization. They can also reach surface waters through surface runoff and, in some cases, contaminate groundwater through leaching. Pesticides can undergo biological, chemical, and/or photolytic degradation in/on plant tissues and other environmental compartments. They may become sorbed to the soil particles depending on the properties of the pesticide and the soil. Multi-media environmental pollution caused by pesticides can have adverse effects on non-target vertebrates, invertebrates, and plants [13, 14].

Multi-media environmental fate and transport models are used to predict the distribution and movement of chemicals in environmental systems with multiple environmental phases and compartments. An overview of the history of multi-media environmental models is provided by Rong-Rong et al. [15]. In the late 1950s, studies on pollutant fate and exposure assessment focused on evaluating the behavior of a single pollutant in a single environmental media. In the 1970s, multi-media mass balance models were developed for regionally and globally distributed metals such as lead, mercury, arsenic, and cadmium. In the late 1970s, studies were conducted on multi-media mass balance models for organic pollutants [15]. Multi-media fate models can quantitatively analyze the intermedia transfers, accumulation, and persistence of pollutants in the environment. The model outcomes can be used to investigate the potential pollution scenarios caused by the chemical, and to analyze the environmental mechanisms underlying the existing pollution conditions.

Pollutant chemicals can be transported to and accumulate in various plant parts, such as roots, stems, leaves, tubers, fruits, and flowers [16]. Several models have been developed to explain the plant-environment relationships regarding chemical pollution. In the 1990s, models were developed to represent the uptake processes of organic chemicals by plants in the environment. Some models focused on root uptake, while others addressed uptake through leaves, and some models considered both pathways [16]. In recent years, models have been developed to describe the interaction of specific crops with environmental pollution [17]. Steady-state calculations are commonly preferred in models due to their simplicity and relatively low data requirements. However, most environmental conditions are characterized using dynamic processes. Additionally, the emission inputs into the real environment are almost never constant [18]. Recently developed plant uptake models take into account dynamic processes [16, 19, 20].

In this study, multi-media environmental models were used to investigate the environmental fate and transport of pesticides that are widely used in fresh vegetable production in Türkiye. First, pesticides frequently exceeding the maximum residue limits in fresh vegetables produced in Türkiye were determined through a literature survey. Then, the physicochemical properties of these pesticides were identi-

fied. The subsequent model-based investigation focuses on examining the environmental risks of commonly used pesticides applied at high doses in Türkiye using multi-media fate models and studying the dynamics of pesticide levels in tomato crops using a crop-specific multi-compartment plant uptake model. The proposed quantitative methods in this study have the potential to be used further in evaluating environmental risks associated with widely used pesticides in Türkiye and addressing the issue of exceeding residue limit values in agricultural products.

MATERIALS AND METHODS

Determination of Pesticides Excessively Used in Fresh Vegetable Production

In this study, scientific publications containing the analysis results of pesticide residues in food consumption products in Türkiye after 2010 were examined. During the literature search, relevant studies were accessed using the terms "pesticide," "residue," or "pesticide residue," and "Türkiye" in databases such as Web of Science, TR-Dizin, ScienceDirect, Google Scholar, and Scopus. Studies conducted before 2010 and residue analyses in animal-derived food products were not included in the survey. Recent studies focusing on cases where maximum residue level (MRL) values were exceeded in agricultural foods were identified. The literature research revealed that pesticide residue analysis studies frequently focused on fresh vegetables, and especially on tomatoes, peppers, and cucumbers. Considering the high daily consumption quantities of these three food products, the pesticides exceeding the MRL values in them were determined and listed. The physicochemical properties influencing the environmental fate of the listed pesticides, such as molecular weight, water solubility, vapor pressure, and half-life in environmental compartments, were compiled from the literature.

Multi-Media Fate Modeling

Multi-media fate models are tools used to estimate the chemical pollution levels in different environmental compartments, quantitatively analyze inter-compartmental transport processes, and describe the accumulation and persistence properties of chemicals. Multi-media models conceptualize different environmental media as interacting compartments with defined volumes and surface areas. The assumption of complete mixing is made for each compartment. Chemical equilibrium processes and advective transport, diffusive transport, and reactive processes are mathematically defined. Mass balance equations are formulated for each compartment and the phases constituting them [21]. The model outputs provide quantitative information on the tendency of chemical pollutants to accumulate and persist in the considered environmental media. The principles of multi-media fate and transport models are detailed by Parnis and Mackay [22]. Depending on the problem to be addressed, multi-media environmental models can be constructed at different scales and at different levels of detail. In this study, calculations were performed using three

different multi-media fate models with varying detail and scope to examine the environmental exposure risks of pesticides used in fresh vegetable production.

Chemical Space Diagram

Chemical space diagram is a conceptual diagram drawn using the output of the simplest possible mass balance equation based on the equilibrium assumption between different phases within a closed system [23]. The diagram illustrates the tendency of chemicals to be present in air, water, or organic matter phases based on their fundamental partitioning characteristics. In the model that generates the diagram, the organic matter phase is represented by octanol, serving as an indicator of the tendency of organic chemicals to associate with solid phases such as soil and sediment. In the calculations, volumes ratios of 656,000:1,300:1 were used to represent the typical volumes of the air, water, and octanol phases, respectively, as suggested in the original study by Gouin et al. [23].

Equilibrium Criterion (EQC) Model

The Equilibrium Criterion (EQC) Model is a multi-media fate model developed by the Canadian Environmental Modeling Centre (CEMC) to be used as a tool for assessing the environmental exposure risks of chemical pollutants [24–27]. The model is developed using fugacity-based mass balance equations to represent the equilibrium and loss processes, advective inputs and inter-compartmental transport of a chemical pollutant. The model allows for calculations of different levels of complexity, but all calculations involve the assumption of steady-state conditions. The modeled environmental system includes compartments of air, water, soil, and sediment. The environmental properties of these compartments, such as volume, interfacial area, density, and organic carbon content, were standardized by the model developers to represent a typical terrestrial region. The model program does not allow users to modify the environmental properties, thereby enabling calculations focused on assessing the characteristics of the chemical pollutant using a "unit world" approach [28]. As input to the model, the physicochemical properties of the pollutant, such as melting point, water solubility, vapor pressure, octanol-water partition ratio (K_{ow}), and half-life in environmental compartments are required. Additionally, emission information needs to be specified.

Plant Uptake Model

In this study, a dynamic multi-compartment plant uptake model, dynamiCROP, was used for the analysis of pesticide residue levels in tomatoes. The DynamicCROP model was developed to evaluate pesticide applications in food crops and exposure effects to pesticide residues, in a life-cycle assessment context [16, 19]. Chemical properties, crop characteristics, and environmental properties constitute the inputs to the model. The model considers inter-compartmental transport and degradation processes. The most fundamental result provided by the model is the harvest fraction (hF), which represents the residue amount in the harvested crop

relative to initially applied pesticide mass [16]. Crop-specific regression models were also developed for dynamiCROP with the aim of reducing the input requirements and facilitating practical usage [29, 30]. The regression models calculate hF values for three different compartments: soil, crop, and crop surface. During the construction of the regression models, parameters that significantly affect the model results were identified. It was observed that the inter-phase partitioning ratios of chemicals, lipid contents of crops, and soil parameters significantly influence the dynamiCROP model output. Therefore, these parameters were assigned as independent variables in the regression equations. In the regression models, the harvest fraction is calculated according to Equations (1) and (2) [29].

$$hF_i = \alpha_{oi} \times \exp(\beta_i (\Delta t \times k_i)) \quad (1)$$

$$hF = hF_{soil} + hF_{crop} + hF_{crop-surface} \quad (2)$$

In Equation (1), hF_i represents the harvest fraction calculated for compartment i ($i = \{soil, crop, crop-surface\}$). Therefore, the parameters α_{oi} , β_i , k_i are computed for each compartment. Regression equations that enable the calculation of these parameters for different plant species are provided by Fantke et al. [29]. Δt is the time (days) passed since the pesticide application. In this study, regression equations developed for tomatoes were used. The parameter α_{oi} represents the initial pesticide amount in the compartment and, for tomatoes, it is dependent on the molecular weight of the pesticide chemical. The k_i value (elimination coefficient) is a measure of the elimination rate from the respective compartment. For the soil compartment, the elimination coefficient is dependent on the persistence value in the soil compartment; and for the crop compartment, it can be calculated using the half-life of the chemical in tomatoes. For the crop-surface compartment, the $\log K_{ow}$ value and molecular weight of the chemical are used to calculate the k_i value. β_i used in Equation (1) is a coefficient that takes a constant value for each crop. Once the hF values are calculated for each compartment, the total harvest fraction (hF) is obtained by adding them (Equation (2)).

RESULTS AND DISCUSSION

Pesticides Exceeding the Residual Limit Values in Fresh Vegetable Crops

In this study, 13 different pesticide residue analysis studies conducted after 2010 were examined. In the published studies, a list of pesticides exceeding the Maximum Residue Level (MRL) was compiled for tomatoes, peppers, and cucumbers produced in Türkiye (Table 1). It was observed that the MRL was exceeded for a total of 34 different pesticide residues. Approximately 44.1% of the chemicals exceeding MRL are included in the banned active substances list prepared by the Ministry of Agriculture and Forestry of the Republic of Türkiye, dated March 3, 2022 [31]. It is expected that the use of these pesticides has been discontinued. Comparing the results of future residue analysis studies with the contents of Table 1 can provide information about the effectiveness of pesticide bans in practice.

The most frequently exceeded MRL values were observed for acetamiprid, chlorpyrifos, and pyridaben (Table 1).

The pesticide types and substance groups that frequently exceeded the MRL in fresh vegetables produced in Türkiye were identified. Additionally, MRL values and pre-harvest intervals for pesticides were compiled from the Ministry of Agriculture and Forestry's Plant Protection Products Database [32] (Table 2). The pre-harvest interval refers to the time between the last pesticide application and harvest. It is determined by the Ministry of Agriculture and Forestry for each pesticide type and plant species [32].

The properties of chemical constituents in pesticides play a crucial role in the environmental fate and plant uptake of these pesticides. The physicochemical properties of pesticides that exceeded MRL at least once in fresh vegetable products (Table 2), were compiled from the Pesticide Properties Database (PPDB) [33] (Table 3). The molecular structures of pollutants determine their partitioning behavior and degradation rates in environmental compartments [34]. The molecular weight of a pollutant affects the inter-phase diffusion coefficient [35]. The interaction between vapor pressure and water solubility values determines the partitioning behavior between air and water phases, while a high $\log K_{ow}$ value indicates a preference for the organic phase (hydrophobicity) compared to the water phase [36]. Half-life represents the time required for the concentration of a chemical in environmental compartments to decrease by half. Since the half-life can vary not only based on the chemical properties but also on the environmental characteristics, the values obtained from the literature should be used as rough estimates for approximate calculations [22].

In addition to their toxic effects, the persistence of pesticides in environmental compartments is also an important factor when regulating their use. A significant portion of the persistent organic pollutants (POP) listed in the Stockholm Convention and subjected to international measures are pesticides with high persistence [34]. Chlorpyrifos, who had been frequently detected to exceed MRL (Table 1) and had been recently banned in Türkiye, is among the chemicals proposed for listing as a POP under the Stockholm Convention [51]. Highly persistent pollutants can reach high concentrations in environmental compartments, thereby increasing exposure risks. When the relationship between the banned status of pesticides and their half-lives in Table 3 is examined, it can be observed that the average half-lives of banned pesticides in all compartments are higher than those of non-banned pesticides. However, the difference between the averages of the two groups is not statistically significant ($p > 0.05$).

Environmental Fate Analysis

Locations of the Pesticides on the Chemical Space Diagram

The positions on the chemical space diagram of all the pesticides that exceeded MRL values in fresh vegetables (Table 3) have been determined (Fig. 1). It can be said that this group of pesticides, which are widely used and can reach high concentrations in vegetable products, tend to distribute between the

Table 1. Pesticide residue analysis studies focusing on fresh vegetables in Türkiye (Published scientific studies since 2010)

Reference	Year	Agricultural product	Pesticides exceeding the MRL	
[37]	2011	Tomato Pepper	Carbendazim Ethion Triazophos Oxamyl	
[38]	2014	Tomato Pepper Cucumber	Acetamiprid Alpha -Endosulfan Beta – Endosulfan Carbendazim Chlorpyrifos Clofentezine Cymoxanil Dichlorvos	Dimethomorph Imidacloprid Malathion Methomyl Oxamyl Tebuconazole Triadimenol Trifloxystrobin
[39]	2016	Tomato	Acetamiprid Beta – Endosulfan Chlorpyrifos Tetradifone	
[40]	2017	Tomato	No active substance exceeding the MRL was detected	
[41]	2018	Tomato Pepper Cucumber	No active substance exceeding the MRL was detected	
[42]	2018	Tomato	Acetamiprid	
[43]	2018	Tomato	Acetamiprid Imazalil Iprodione	
[44]	2019	Tomato Pepper	Acetamiprid Bromopropylate Chlorpyrifos Cyproconazole Dichlorvos Etofenprox Etoxazole Fenarimol	Fenazaquin Formetanate -HCl Methomyl Metrafenone Omethoate Pendimethalin Pyridaben
[45]	2016	Tomato Pepper	No active substance exceeding the MRL was detected	
[46]	2021	Cucumber	Imidacloprid	
[47]	2022	Pepper	Acetamiprid Chlorpyrifos Etofenprox Etoxazole Fenazaquin Formetanate -HCl Methomyl Metrafenone Pyridaben	
[48]	2022	Tomato Cucumber	Pyrimiphos Chlormequat chloride Pyridaben Chlormequa	
[49]	2022	Pepper Cucumber	Metrafenone Pyridaben	

Table 2. MRL values and pre-harvest waiting periods of pesticides that exceed residue limit values in fresh vegetables produced in Türkiye [32]

Pesticide active substance	Pesticide type	Substance group	MRL (mg/kg)			MRL (mg/a pre-harvest waiting period kg)		
			Tomato	Pepper	Cucumber	Tomato	Pepper	Cucumber
Acetamiprid	Insecticide	Neonicotinoid	0.5	0.3	0.3	3 days	3 days	3 days
Alpha - Endosulfan	Insecticide	Organochloride	Banned (2010)			–	–	–
Beta - Endosulfan	Insecticide	Organochloride	Banned (2010)			–	--	–
Bromopropylate	Acaricide	Diphenole	Banned (2011)			–	–	–
Carbendazim	Fugacide	Carbamate	Banned (2011)			–	–	–
Chlormequat chloride	Plant Growth Regulator	Quarternary ammonium compound	–	–	–	–	–	–
Chlorpyrifos	Insecticide	Organophosphate	Banned (2020)			–	–	–
Clofentezine	Acaricide	Tetrazine	–	–	0.2			3 days
Cymoxanil	Fugacide	Cyanoacetamide	0.4	–	0.08	3 days	–	3 days
Cyproconazole	Fugacide	Triazole	No data available			No data available		
Dichlorvos	Insecticide	Insecticide	Banned (2011)			–	–	–
Dimethomorph	Fugacide	Morpholine	1	1	0.5	7 days	1 day	7 days
Ethion	Insecticide	Organophosphate	Banned (2010)			–	–	–
Etofenprox	Insecticide	Pyrethroid	0.7	–	–	3 days	–	–
Etoxazole	Acaricide	Diphenyl	0.07	0.01	0.02	3 days	3 days	3 days
Fenarimol	Fugacide	Pyrimidine	Banned (2011)			–	–	–
Fenazaquin	Acaricide	Quinazoline	0.05	–	–	3 days	–	–
Formetanate -HCl	Insecticide	Formamidine	0.3	–	0.01	14 days	–	7 days
Imazalil	Fugacide	İmidazole	0.3	0.01	0.5	3 days	3 days	3 days
Imidacloprid	Insecticide	Neonicotinoid	0.5	–	–	–	–	–
Iprodione	Fugacide	Dichlorophenyl	Banned (2018)			–	–	–
Malathion	Insecticide	Organophosphate	0.02	–	–	7 days	–	–
Methomyl	Insecticide	Carbamate	Banned (2021)			–	–	–
Metrafenone	Fugacide	Benzophenone	0.6	2	0.5	3 days	3 days	1 day
Omethoate	Insecticide	Organophosphate	Banned (2012)			–	–	–
Oxamyl	Insecticide	Carbamate	Banned (2012)			–	–	–
Pendimethalin	Herbicide	Dinitroaniline	0.05	–	–	Pre-planting	–	–
Pirimiphos - Methyl	Insecticide	Organophosphate	0.01	–	0.01	7 days	–	7 days
Pyridaben	Insecticide	Pyridazinone	0.15	0.3	0.15	3 days	3 days	3 days
Tebuconazol	Fugacide	Triazole	0.9	0.6	0.6	7 days	3 days	3 days
Tetradifone	Acaricide	Diphenyl	Banned (2011)			–	–	–
Triazophos	Insecticide	Organophosphate	Banned (2010)			–	–	–
Triadimenol	Fugacide	Triazole	Banned (2021)			–	–	–
Trifloxystrobin	Fugacide	Strobilurin	0.7	0.4	0.3	3 days	3 days	3 days

water and octanol phases instead of being present in the air. The distribution characteristics between the water and octanol phases vary depending on the values of the octanol-water partition ratio for these chemicals. However, most pesticides are in the intermediate region where significant distribution between both the water and octanol phases is expected.

The positions of acetamiprid, chlorpyrifos, and pyridaben, which frequently exceeded the MRL values in recent residue analysis studies (Table 1), are highlighted in red on the chemical space diagram (Fig. 1). These three pesticides are in three separate regions on the diagram, indicating that their environmental partitioning behaviors are different.

Table 3. Physicochemical properties of pesticides that exceed residue limit values in fresh vegetables produced in Türkiye [33]

Pesticide active substance	Molecular weight (g/mol)	Octanol– water partition ratio ($\log K_{ow}$)	Solubility in water (mg/l, 20 °C)	Vapour pressure (mPa, 20 °C)	Half-life (days)		
					Soil	Water	Sediment
Acetamiprid	222.67	0.8	2950	1.73×10^{-04}	1.6	4.7	337.5*
Alpha - Endosulfan	406.93	4.74	0.32	8.3	50	–	–
Beta - Endosulfan	406.93	3.83	0.45	–	–	–	–
Bromopropylate	428.1	5.4	0.1	0.011	59	4	63
Carbendazim	191.21	1.48	8.0	0.09	40	7.9	33.7
Chlormequat chloride	158.07	-3.47	886000	1.0×10^{-03}	27.4	0.5	3.75
Chlorpyrifos	350.58	4.7	1.05	1.43	386	5	36.5
Clofentezine	303.15	4.09	0.0342	6.0×10^{-04}	69.8	2.1	9.6
Cymoxanil	198.18	0.67	780	0.15	1.7	0.3	0.3
Cyproconazole	291.78	3.09	93	0.026	142	–	1000
Dichlorvos	220.98	1.9	18000	2100	2	–	0.22
Dimethomorph	387.86	2.68	28.95	9.7×10^{-04}	72.7	10	38
Ethion	384.48	5.07	2	0.2	90	–	–
Etofenprox	376.49	6.9	0.0225	8.13×10^{-04}	11	5.7	13.3
Etoxazole	359.42	5.52	0.07	0.007	19.3	1.45	79.5
Fenarimol	331.20	3.69	13.7	0.065	250	4	Stabil
Fenazaquin	306.40	5.51	0.102	1.90×10^{-02}	45	–	–
Formetanate -HCl	257.8	-0.0014	822000	1.60×10^{-03}	12.9	0.3	0.3
Imazalil	297.18	2.56	184	0.158	76.3	7.8	117
Imidacloprid	255.66	0.57	610	4.0×10^{-07}	191	30	129
Iprodione	330.17	3.0	6.8	0.0005	36.2	2.0	4.0
Malathion	330.36	2.75	148	3.1	0.17	0.4	0.4
Methomyl	162.21	0.09	55000	2.13×10^{-06}	7	2.9	3.7
Metrafenone	409.27	4.3	0.492	0.153	200.9	3.9	9.3
Omethoate	213.2	-0.9	500000	19.0	0.1	–	4.5
Oxamyl	219.26	-0.44	184100	0.018	5.3	–	0.7
Pendimethalin	281.31	5.4	0.33	3.34	182.3	4	16
Pirimiphos - Methyl	305.33	4.2	11	2.00×10^{-03}	39	–	–
Pyridaben	364.93	6.37	0.022	0.001	55	1.18	17.5
Tebuconazol	307.82	3.7	36	1.30×10^{-03}	63	42.6	365
Tetradifone	356.06	4.61	0.078	3.20×10^{-05}	112	–	–
Triazophos	313.3	3.55	35	1.33	44	35	35
Triadimenol	295.76	3.18	72	0.0005	250	53	91
Trifloxystrobin	408.37	4.5	0.61	3.40×10^{-03}	0.34	1.1	2.4

*: Acetamiprid sediment half-life value was obtained from EPI Suite [50].

Acetamiprid has the lowest $\log K_{ow}$ value among the three pesticides and its vapor pressure is low. Therefore, it is expected to be present in the water phase. Acetamiprid's relatively high solubility increase its likelihood of transport into plants through water uptake from soil. Additionally, the risk of surface water and groundwater pollution by Acetamiprid should be considered.

Chlorpyrifos is located to the right of the middle region

of the diagram, indicating a tendency for presence in the octanol phase with non-negligible partitioning in the air and water phases (Fig. 1). Chlorpyrifos has a higher air-water partition coefficient compared to the other pesticides shown in the diagram. Due to its high half-life values in both sediment and soil, Chlorpyrifos is expected to remain and accumulate in the soil compartment where it is applied. Chlorpyrifos is a widely used pesticide that can cause environmental contamination in air, water, and soil, and it has

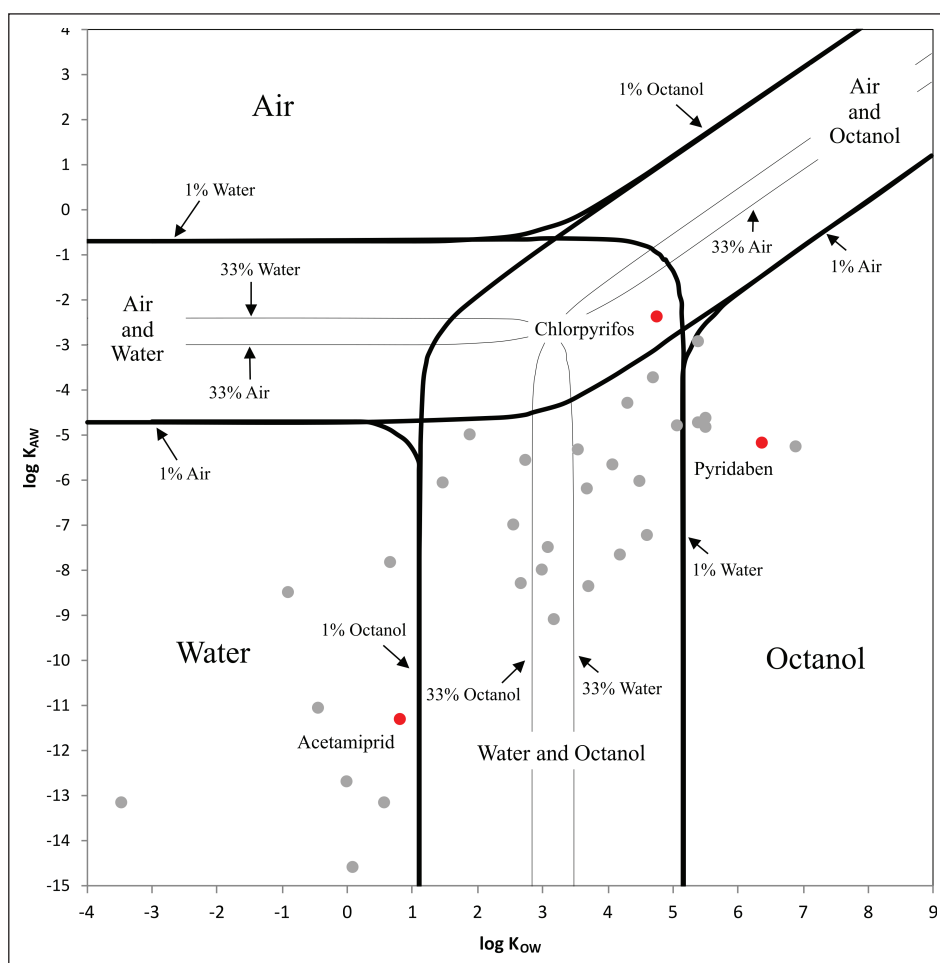


Figure 1. Chemical Space Diagram (Volatile substances tend to locate on the upper-left, water-soluble substances tend to locate on the lower-left, hydrophobic substances tend to locate on the lower-right [23]. The lines indicate constant percentages between the air, water, and octanol phases).

been associated with various health issues, including endocrine disruption [52]. Its use in Türkiye has been banned.

Pyridaben has the highest $\log K_{OW}$ value among these three chemicals. It is expected to tend to be present in the octanol phase. This characteristic may contribute to its sorption to soil and accumulation in the lipid tissues of plants. However, a more detailed modeling approach is necessary to assess the risk associated with its transport to surface water and groundwater.

Equilibrium Criterion (EQC) Model Results

Acetamiprid, chlorpyrifos, and pyridaben were subjected to Level III calculations using the EQC model. Level III mass balance calculations assume a steady-state condition but do not assume equilibrium between compartments, taking into account advection, diffusion, and reactive transfer processes. The properties of the Level III standard evaluative environment of the EQC model are given in Hughes et al. [27]. It was assumed that the three modeled pesticides enter the standard environmental system through emission to soil. The same emission rate (1000 kg/hour) was assigned to each pesticide, and the results were evaluated comparatively. The half-lives of acetamiprid, chlorpyrifos, and pyrida-

ben were assigned the values of 3.36, 4.38, and 6.06 hours, respectively, as obtained from EPI Suite [50]. The modeling results are summarized in Figure 2–5.

The mass distributions of the three pesticides among the environmental compartment were calculated (Fig. 2). Soil, the compartment where the emissions occur, contained the largest mass fraction for all the pesticides. Acetamiprid was found in the water compartment in significantly high amounts, and it had almost no presence in the air compartment. The pesticide that had the largest fraction in the soil compartment was Chlorpyrifos. Also, a significant amount of Chlorpyrifos was present in the air compartment. Pyridaben's compartmental mass distribution was similar to Chlorpyrifos, but it had a higher fraction in water and a lower fraction in air. These results were in accordance with the information obtained from the chemical space diagram. However, none of the pesticides were distributed to the sediment compartment in significant amounts. This result is related with the intermedia mass transfer properties of the pesticides. And, it can change if there are direct emissions to the compartments other than soil. Also, although the total mass in the sediment compartment is low, since sediment volume is small compared to the other compartments, the concentrations may still reach dangerous levels.

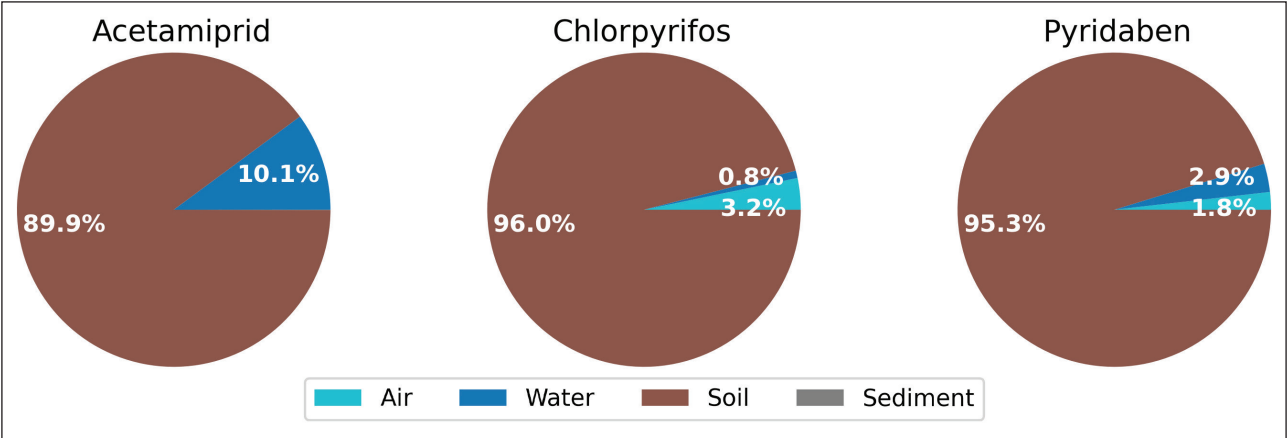


Figure 2. Compartmental mass distributions of the pesticides in the EQC model environment.

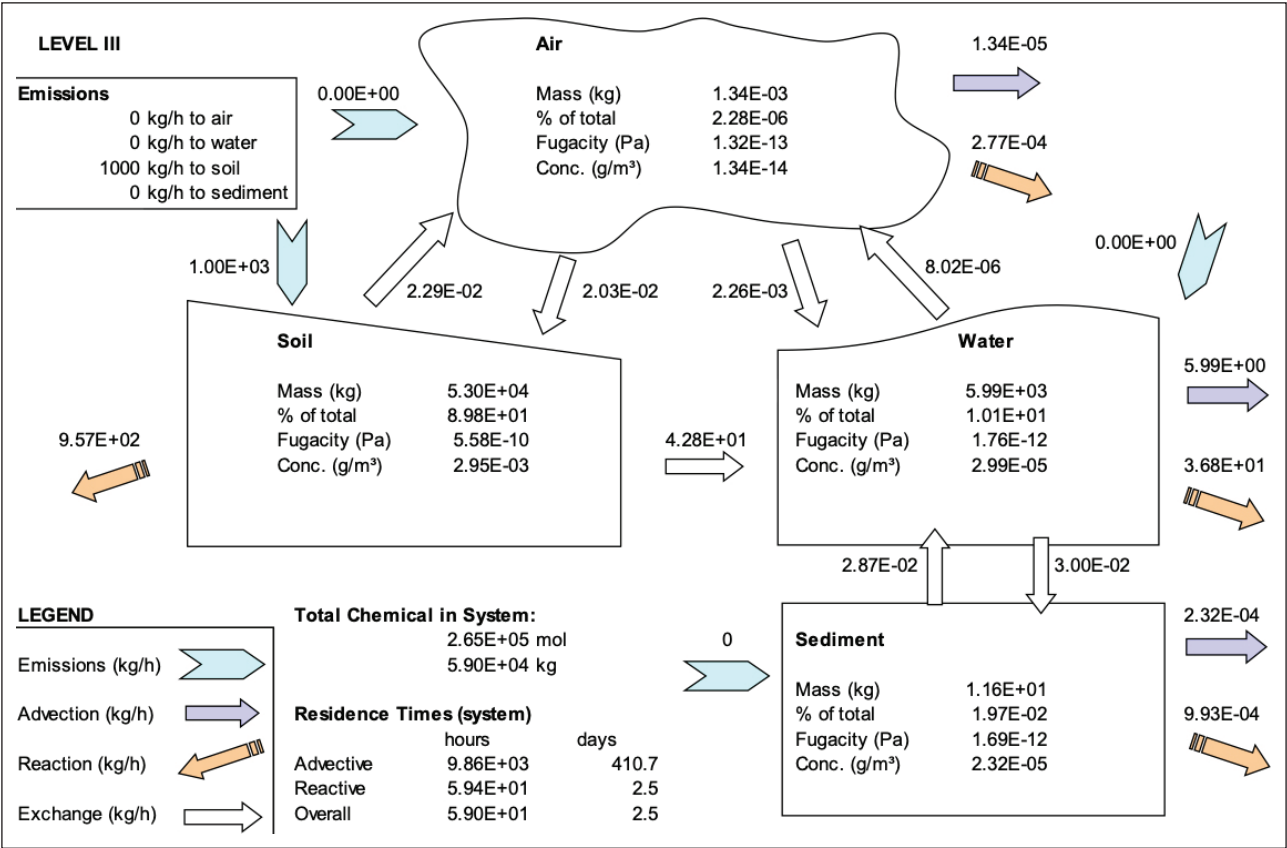


Figure 3. EQC model results for acetamiprid.

Mass transport rates and the residence times calculated by the EQC model are provided in the summary diagrams in Figure 3–5. Acetamiprid’s overall persistence in the EQC environment is 2.5 days, lower than the other two pesticides (Fig. 3). When the model results for Chlorpyrifos is examined, it’s high soil-to-air transfer can be seen (Fig. 4). Correspondingly, there are significant reactive losses in the air compartment. Despite its high hydrophobicity, chlorpyrifos tends to transfer to the air compartment, increasing its advection and reactive losses in the system, resulting in a total persistence value of 7.5 days. The intercompartmental distribution behavior of pyridaben is similar to Chlorpyrifos (Fig. 5). However, it shows less tendency for transfer to the air compartment,

resulting in relatively higher accumulation in the water and sediment compartments. This limits the advection and reactive losses, causing pyridaben to have a slightly higher total persistence in the system compared to chlorpyrifos. The total persistence of pyridaben is calculated as 11.9 days. The main loss mechanism is reaction for all the three pesticides. The net intermedia transfer rates of the three pesticides are given in Table 4 as a fraction of the total emission rate (1000 kg/h). A comparative examination of the intermedia transfer rates reveals the dominant direction of movement for the pesticides after being released to the soil compartment. It is seen that the dominant movement of acetamiprid in

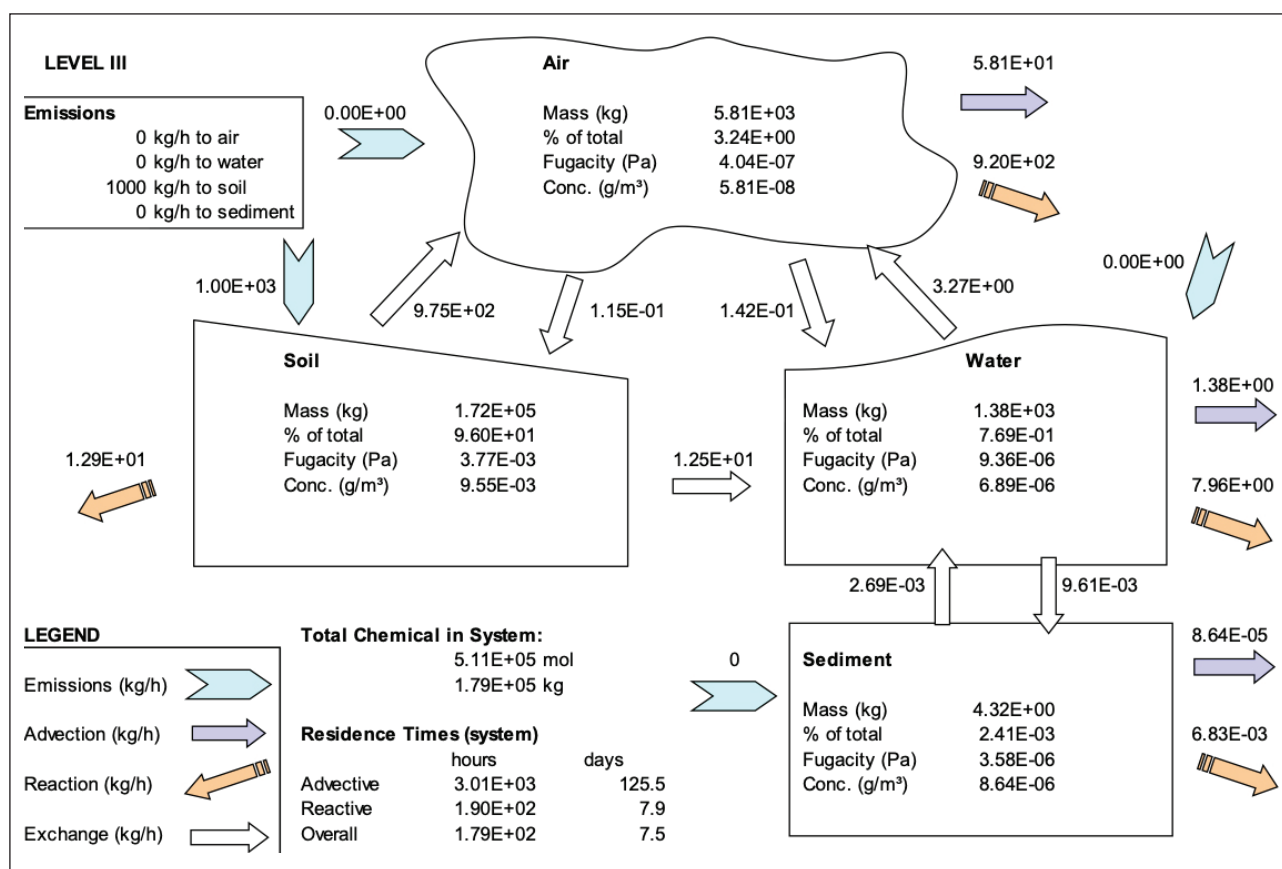


Figure 4. EQC model results for chlorpyrifos.

Table 4. Net intermedia transport rates for the three pesticides after being emitted to soil (fractional rates to the total emission rate) (EQC Model Results)

	Acetamiprid	Chlorpyrifos	Pyridaben
Soil-to-air	$2.54E-06$	97.47%	63.76%
Soil-to-water	4.28%	1.25%	21.92%
Water-to-air	$-2.25E-06$	0.31%	0.60%
Water-to-sediment	$1.23E-06$	$6.92E-06$	$1.51E-05$

the environmental system is from soil to water. Acetamiprid experiences very limited transfers between the other compartments. The potential of acetamiprid to pollute surface waters and groundwater should be further investigated using more detailed models. For chlorpyrifos, the dominant transfer is from soil to air, where it is lost from the system mainly by degradation reactions and advection. Although degradation in air is the main loss mechanism for chlorpyrifos, advective loss through atmospheric transport is not negligible. Long range transport potential of chlorpyrifos through atmosphere is a significant concern supported by monitoring and modeling studies [53]. Long-range transport potential is one of the criteria for chemicals to be classified as a persistent organic pollutant (POP), and chlorpyrifos is a POP candidate under the Stockholm Convention [51]. For pyridaben, soil to air transfer is dominant, but its soil to water transfer is also significant. Since EQC model

results indicates higher persistence for pyridaben compared to chlorpyrifos, the potential for pyridaben to reach remote regions through atmospheric and aquatic transport should be further investigated.

Time Dependent Residue Values in Tomato

DynamicCROP model's regression equations were used to calculate the time-dependent harvest fractions for acetamiprid, chlorpyrifos, and pyridaben in tomato products (Fig. 6). Acetamiprid's harvest fraction, and consequently, its residue amount, exhibits a faster decline compared to the others. On the other hand, acetamiprid's initial harvest fraction is higher compared to the other two pesticides. This is due to its lower molecular weight value, which facilitates its incorporation to the tomatoes after being applied. As a result of the high persistence values of chlorpyrifos and pyridaben, a slower decrease in the harvest fraction is observed for these two chemicals. In tomato production, the recommended pre-harvest waiting period for acetamiprid and pyridaben is three days, and the MRL values are 0.5 and 0.15 mg/kg, respectively (Table 2). After three days, a decrease in residue levels is observed for all pesticides. However, it is predicted that Acetamiprid's residue rate will still be relatively high when compared to the initial residue values. For these two pesticides, re-evaluating application doses and pre-harvest waiting periods through more specific model calculations and controlled experiments can provide useful information for preventing the exceedance of MRL values.

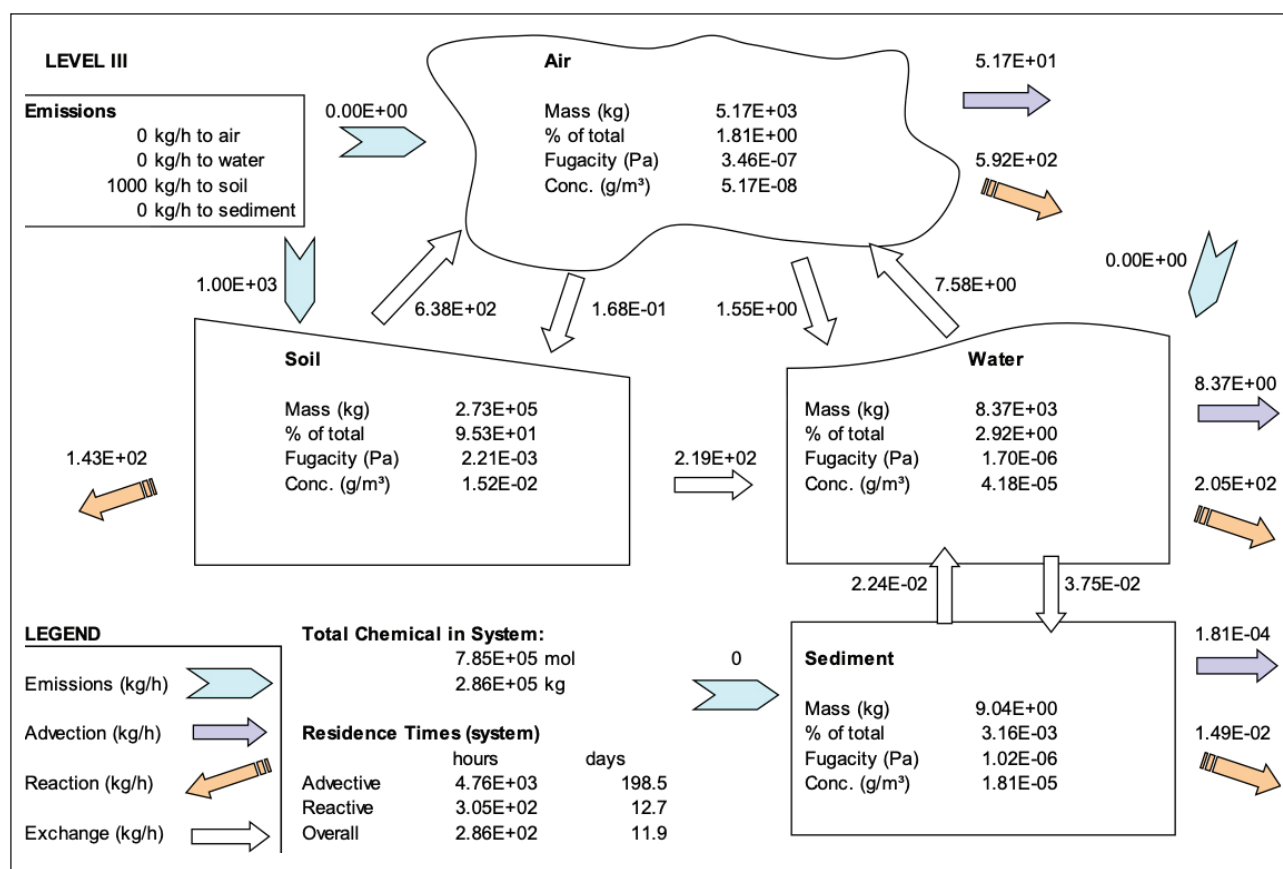


Figure 5. EQC model results for pyridaben.

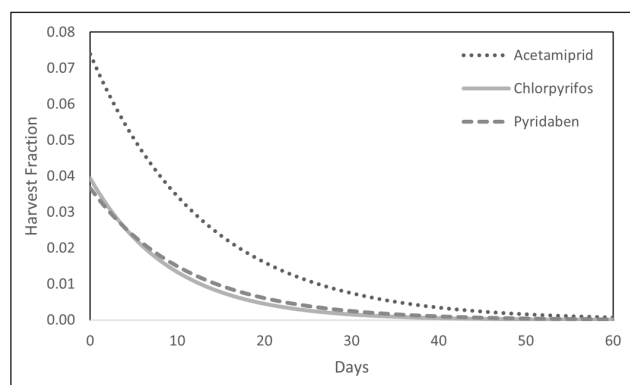


Figure 6. Time dependent harvest fractions estimated by the plant uptake model.

CONCLUSION

This study presents modeling methods for assessing the environmental exposure risks of pesticides. Pesticides, widely utilized in agricultural practices due to their efficacy and cost-effectiveness, can pose potential risks to both the environment and human health when misused or applied improperly. Also, the residue levels exceeding the regulated MRL values causes significant economic losses. In the reviewed scientific studies, there were many instances of pesticide residues exceeding MRL values and banned pesticides were also identified in the products. This indicates that existing preventive measures may not be entirely adequate.

In the first part of this study, recent published research on pesticide residues in fresh vegetables produced in Türkiye was examined. The reviewed research findings showed a significant occurrence of pesticide residues exceeding the MRL values. The frequent exceedance of MRLs in agricultural products can lead to health risks for consumers and may cause environmental problems in agricultural regions. Moreover, the disposal of agricultural products containing pesticide residues above permissible levels, results in economic losses. The quantity of pesticide residues in fresh vegetable products is influenced by various factors, including the mode of pesticide application, dosage, timing, and the physicochemical properties of the pesticide active ingredients. In this study, the physicochemical properties determining the fate of problematic pesticides in environmental compartments and plants, along with the recommended pre-harvest intervals, were identified referring to up-to-date sources.

The second part of the study involved conducting calculations to demonstrate the applicability of multi-media fate models in evaluating the environmental and health risks of pesticides. A chemical space diagram was used to assess the environmental partitioning behavior of the pesticides. The diagram provided valuable insights into how pesticides would distribute among air, water, and solid organic phases upon release into the environment. It was observed that most pesticides associated with exceeding regulatory limits tend to accumulate in the water and organic solid phases. Further detailed evaluations were performed for three pesticides

(acetamiprid, chlorpyrifos, pyridaben) that were found to exceed MRL values relatively more frequently. These three pesticides have different locations in the chemical space diagram. Acetamiprid tends to be present in the water phase, while pyridaben shows an affinity for the organic solid phase. On the other hand, chlorpyrifos, which is currently banned from use in Türkiye, demonstrates a relatively higher affinity for the air phase compared to the other pesticides.

The Equilibrium-Criterion Model (EQC), which includes the air, water, soil, and sediment compartments, were applied to assess the multi-media environmental fate and transport characteristics of the selected three pesticides. Level III steady-state model calculations were performed under the same environmental conditions and emission scenarios, enabling a comparative evaluation. The accumulation levels in the four compartments, inter-compartmental transfer rates, and losses from the system due to advective and reactive processes were calculated for all three pesticides. It was observed that all three pesticides reached the highest accumulation in the soil compartment, where they were initially released to the environment. When comparing the environmental persistence of the three pesticides, the order is as follows: pyridaben > chlorpyrifos > acetamiprid. Degradation reactions were identified as the main loss process for all pesticides. Despite chlorpyrifos having higher reaction half-lives in water and soil, pyridaben showed higher environmental persistence. This can be attributed to pyridaben's higher hydrophobicity but lower volatility compared to chlorpyrifos. The use of more detailed multi-media fate models based on EQC but tailored to represent specific agricultural regions can help assess pesticide related environmental pollution. The model results can guide field and sampling studies. Model simulations can be conducted to contribute to agricultural pollution management efforts.

Finally, calculations were performed using a dynamic plant uptake model, called dynamiCROP, for the selected three pesticides. In these calculations, dynamiCROP's regression equations were used, and the time-dependent changes in the pesticides' harvest fractions were compared. The results of the calculations indicated that acetamiprid had a higher initial uptake into tomatoes compared to the other two pesticides. This finding was interpreted to be due to acetamiprid's relatively lower molecular weight, which may result in higher diffusion into tomatoes after application. On the other hand, acetamiprid residues in tomatoes were found to decline faster than the other two pesticides. The dynamics of chlorpyrifos and pyridaben residues were similar to each other. Conducting simulations using the full version of the dynamiCROP model would allow more detailed evaluations. Additionally, similar simulations can help in the determination of the pre-harvest waiting time and the initial pesticide dosage in agricultural applications.

The use of environmental fate models in the production and authorization processes of pesticides can reveal the potential environmental issues at an early stage enabling the application of preventive measures. This approach can provide guidance when determining the pesticide's dosage, ap-

plication method, pre-harvest waiting period, and potential residue levels. Furthermore, the integration of environmental fate and transport models with plant uptake models can enable comprehensive analyses at field and regional scales. Similar models can be employed to aid remediation plans in regions where pollution problems exist.

DATA AVAILABILITY STATEMENT

The author confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

REFERENCES

- [1] FAO, "FAOSTAT: Production: Crops and livestock products," 2023. <https://www.fao.org/faostat/en/#data/QCL>.
- [2] FAO, "FAOSTAT: Trade: Crops and livestock products," 2023. <https://www.fao.org/faostat/en/#data/TCL>.
- [3] S. Kaymak, A. Özdem, A. Karahan, B. Özercan, P. Aksu, A. Aydar, M. Kodan, A. Yılmaz, M. S. Başaran, Ü. Asav, P. Erdoğan, and Y. Güler, "Ülkemizde zirai mücadele girdilerinin değerlendirilmesi," T.C. Gıda Tarım Ve Hayvancılık Bakanlığı Tarımsal Araştırmalar ve Politikalar Genel Müdürlüğü, Ankara, 2015. [CrossRef]
- [4] F. N. Doğan and M. E. Karpuzcu, "Current status of agricultural pesticide pollution in Turkey and evaluation of alternative control methods," Pamukkale University Journal of Engineering Science, Vol. 25(6), pp. 734–747, 2019.
- [5] N. Delen, E. Durmuşoğlu, A. Güncan, N. Güngör, C. Turgut, and A. Burçak, "Türkiye'de pestisit kullanımı, kalıntı ve organizmalarda duyarlılık azalışı sorunları," in Türkiye Ziraat Mühendisliği VI: Teknik Kongre, 2005, pp. 1–21.
- [6] European Commission, "2021 annual report: Alert and cooperation Network," 2022.
- [7] RASFF, "The rapid alert system for food and feed - annual report 2020," 2021.
- [8] RASFF, "RASFF Window," 2023. <https://webgate.ec.europa.eu/rasff-window/screen/search>.
- [9] O. Tiryaki, "Türkiye'de yapılan pestisit kalıntı analiz ve çalışmaları," Erciyes Üniversitesi Fen Bilimi Enstitüsü Fen Bilimleri Dergisi, Vol. 32(1), pp. 72–80, 2016.

- [10] M. Tözün, and G. Akar, “Türkiye’de gıda numunelerinde pestisit kalıntıları üzerine 2010 yılı ulusal literatürün incelenmesi,” *ESTÜDAM Halk Sağlığı Dergisi*, Vol. 7(1), pp. 177–191, 2022. [\[CrossRef\]](#)
- [11] M. A. Babayigit, Ö. F. Tekbaş, and H. Çetin, “Public health effects of pesticides used in pest management and precautions for the protection,” *TAF Preventive Medicine Bulletin*, Vol. 13(5), pp. 405–412, 2014. [\[CrossRef\]](#)
- [12] T. M. Osaili, M. S. Al Sallagi, D. K. Dhanasekaran, W. A. M. Bani Odeh, H. J. Al Ali, A. A.S.A. Al Ali, L. C. Ismail, K. O. Al Mehri, V. A. Pisharath, R. Holley, and R. S. Obaid, “Pesticide residues in fresh vegetables imported into the United Arab Emirates,” *Food Control*, Vol. 133, 2022. [\[CrossRef\]](#)
- [13] Y. Karsavuran, S. Erkan, and N. Tosun, “Pestisit uygulamalarının toprak üzerindeki olumsuz etkileri,” in 4. Ulusal Ekoloji ve Çevre Kongresi, pp. 377–382, 2001.
- [14] M. Tudi, H. D. Ruan, L. Wang, J. Lyu, R. Sadler, D. Connell, C. Chu, and D. T. Phung, “Agriculture development, pesticide application and its impact on the environment,” *International Journal of Environmental Research and Public Health*, Vol. 18(3), pp. 1–24, 2021. [\[CrossRef\]](#)
- [15] Z. Rong-Rong, Z. Che-Sheng, H. Zhong-Peng, and S. Xiao-Meng, “Review of environmental multimedia models,” *Environmental Forensics*, Vol. 13(3), pp. 216–224, 2012. [\[CrossRef\]](#)
- [16] P. Fantke, R. Charles, L. F. de Alencastro, R. Friedrich, and O. Jolliet, “Plant uptake of pesticides and human health: Dynamic modeling of residues in wheat and ingestion intake,” *Chemosphere*, Vol. 85(10), pp. 1639–1647, 2011. [\[CrossRef\]](#)
- [17] S. Trapp, “Calibration of a plant uptake model with plant- and site-specific data for uptake of chlorinated organic compounds into radish,” *Environmental Science & Technology*, Vol. 49(1), pp. 395–402, 2015. [\[CrossRef\]](#)
- [18] A. Rein, C. N. Legind, and S. Trapp, “New concepts for dynamic plant uptake models,” *SAR and QSAR in Environmental Research*, Vol. 22(1–2), pp. 191–215, 2011. [\[CrossRef\]](#)
- [19] P. Fantke, R. Juraske, A. Antón, R. Friedrich, and O. Jolliet, “Dynamic multicrop model to characterize impacts of pesticides in food,” *Environmental Science & Technology*, Vol. 45(20), pp. 8842–8849, 2011. [\[CrossRef\]](#)
- [20] R. K. Goktas and M. M. Aral, “Integrated dynamic modeling of contaminant fate and transport within a soil–plant system,” *Vadose Zone Journal*, Vol. 10(4), pp. 1130–1150, 2011. [\[CrossRef\]](#)
- [21] M. Macleod, M. Scheringer, T. E. Mckone, and K. Hungerbühler, “The state of multimedia mass-balance modeling in environmental science and decision-making,” *Environmental Science & Technology*, Vol. 44, pp. 8360–8364, 2010. [\[CrossRef\]](#)
- [22] J. M. Parnis, and D. “Mackay, multimedia environmental models: The fugacity approach (3rd ed.),” CRC Press, 2020. [\[CrossRef\]](#)
- [23] T. Gouin, D. Mackay, E. V. A. Webster, and F. Wania, “Screening chemicals for persistence in the environment,” *Environmental Science & Technology*, Vol. 34(5), pp. 881–884, 2000. [\[CrossRef\]](#)
- [24] D. Mackay, A. Di Guardo, S. Paterson, G. Kicsi, and C. Cowan, “Assesing the fate of new and existing chemicals: A five-stage process,” *Environmental Toxicology and Chemistry*, Vol. 15(9), pp. 1618–1626, 1996. [\[CrossRef\]](#)
- [25] D. Mackay, A. Di Guardo, S. Paterson, and C. E. Cowan, “Evaluating the environmental fate of a variety of types of chemicals using the EQC model,” *Environmental Toxicology and Chemistry*, Vol. 15(9), pp. 1627–1637, 1996. [\[CrossRef\]](#)
- [26] D. Mackay, A. Di Guardo, S. Paterson, G. Kicsi, C. Cowan, and D. Kane, “Assesment of chemical fate in the environment using evaluative, regional and local-scale models: Illustrative application to chlorobenzene and linear alkylbenzene sulfonates,” *Environmental Toxicology and Chemistry*, Vol. 15(9), pp. 1638–1648, 1996. [\[CrossRef\]](#)
- [27] L. Hughes, D. Mackay, D. E. Powell, and J. Kim, “An updated state of the science eqc model for evaluating chemical fate in the environment: Application to D5 (decamethylcyclopentasiloxane),” *Chemosphere*, Vol. 87(2), pp. 118–124, 2012. [\[CrossRef\]](#)
- [28] D. Mackay, “Finding fugacity feasible, fruitful, and fun,” *Environmental Toxicology and Chemistry*, Vol. 23(10), pp. 2282–2289, 2004. [\[CrossRef\]](#)
- [29] P. Fantke, P. Wieland, R. Juraske, G. Shaddick, E. S. Itoiz, R. Friedrich, and O. Jolliet, “Parameterization models for pesticide exposure via crop consumption,” *Environmental Science & Technology*, Vol. 46(23), pp. 12864–12872, 2012. [\[CrossRef\]](#)
- [30] P. Fantke, P. Wieland, C. Wannaz, R. Friedrich, and O. Jolliet, “Dynamics of pesticide uptake into plants: From system functioning to parsimonious modeling,” *Environmental Modelling & Software*, Vol. 40, pp. 316–324, 2013. [\[CrossRef\]](#)
- [31] Turkish Ministry of Food Agriculture and Livestock, “Yasaklı veya Kısıtlı Aktif Madde Listeleri,” PPP Database Application, 2022. <https://bku.tarimorman.gov.tr/AktifMadde/YasakliKisitliExcelFileList?csrt=11147665390916831822>.
- [32] Turkish Ministry of Food Agriculture and Livestock, “Plant Protection Products Database,” 2023. <https://bku.tarimorman.gov.tr/Duyuru/Bulten?csrt=11147665390916831822>.
- [33] Pesticide Properties DataBase, “Pesticide Properties DataBase,” 2023. <http://sitem.herts.ac.uk/aeru/ppdb/>.
- [34] R. K. Göktaş and M. Macleod, “Hazardous pollutants in the water environment,” in *Hazardous Pollutants in Biological Treatment Systems*, 2017, pp. 17–67. [\[CrossRef\]](#)

- [35] H. Hemond, and E. Fechner, "Chemical fate and transport in the environment (3rd ed.)," Elsevier, 2015.
- [36] R. K. Göktaş, and M. Macleod, "Hazardous pollutants in the water environment," in Hazardous Pollutants in Biological Treatment Systems, F. Çeçen, and U. Tezel, (Eds.), IWA Publishing, 2017, pp. 17–67.
- [37] N. Ersoy, Ö. Tatlı, S. Özcan, E. Evcil, L. Ş. Coşkun, and E. Erdoğan, "Determination of pesticide residues in some vegetable species by LC-MS/MS and GC-MS," Selçuk Tarım ve Gıda Bilim. Dergisi, Vol. 25, pp. 79–85, 2011.
- [38] G. T. Bakirci, D. B. Yaman Acay, F. Bakirci, and S. Ötleş, "Pesticide residues in fruits and vegetables from the Aegean region, Turkey," Food Chemistry, Vol. 160, pp. 379–392, 2014. [CrossRef]
- [39] M. Yalçın, and C. Turgut, "Determination of Pesticide Residues in Tomatoes Collected from Aydın Province of Turkey," Scientific Papers Series A. Agronomy, Vol. LIX, pp. 547–551, 2016.
- [40] B. Polat, and O. Tiryaki, "Çanakkale ili açık alan domates yetiştiriciliğinde pestisit kalıntılarının quechers yöntemi ile araştırılması," ÇOMÜ Ziraat Fakültesi Dergisi, Vol. 6, pp. 71–79, 2018.
- [41] T. Kaya, "İzmir ilindeki üç halk pazarından alınan meyve ve sebze örneklerindeki pestisit kalıntı miktarlarının araştırılması," [Master Thesis], Sıtkı Koçman Üniversitesi, Fen Bilimleri Enstitüsü, 2018. [CrossRef]
- [42] T. Balkan, and K. Kara, "Tokat ilinde tüketime sunulan domateslerde neonikotinoid grubu insektisitlerin kalıntı düzeylerinin belirlenmesi üzerine araştırmalar," Gaziosmanpaşa Bilimsel Araştırmalar Dergisi, Vol. 8, pp. 50–58, 2019.
- [43] F. Hepsağ, and T. Kizildeniz, "Pesticide residues and health risk appraisal of tomato cultivated in greenhouse from the mediterranean region of Turkey," Environmental Science and Pollution Research, Vol. 28(18), pp. 22551–22562, 2021. [CrossRef]
- [44] U. Çiftçi, "Çanakkale pazarında satılan domates ve biberlerde pestisit kalıntılarının araştırılması," [Master Thesis], Çanakkale Onsekiz Mart Üniversitesi, Fen Bilimleri Enstitüsü, 2019.
- [45] D. K. Soydan, N. Turgut, M. Yalçın, C. Turgut, P. Binnur, and K. Karakuş, "Evaluation of pesticide residues in fruits and vegetables from the Aegean region of Turkey and assessment of risk to consumers," Environmental Science and Pollution Research, Vol. 28, pp. 27511–27519, 2021. [CrossRef]
- [46] İ. Toptancı, M. Kiralan, and M. F. Ramadan, "Levels of pesticide residues in fruits and vegetables in the Turkish domestic markets," Environmental Science and Pollution Research, Vol. 28, pp. 39451–39457, 2021. [CrossRef]
- [47] İ. Yıldırım, and U. Çiftçi, "Monitoring of pesticide residues in peppers from Çanakkale (Turkey) public market using QuEChERS method and LC-MS/MS and GC-MS/MS detection," Environmental Monitoring and Assessment, Vol. 194, Article 570, 2022. [CrossRef]
- [48] B. Çakmak Sancar, M. Akhan, M. Öztürk, and Ö. Ergün, "İstanbul'da satışa sunulan bazı meyve ve sebzelerde LC-MS/MS ile pestisit kalıntılarının tespiti," Harran Tarım ve Gıda Bilim. Dergisi, Vol. 26, pp. 303–315, 2022. [CrossRef]
- [49] T. Balkan and K. Kara, "Determination of pesticide residues and risk assessment in some vegetables grown in Tokat province," Bitki Koruma Bülteni, Vol. 62, pp. 26–35, 2022. [CrossRef]
- [50] "EPI Suite™-Estimation Program Interface | US EPA," 2023. <https://www.epa.gov/tsca-screening-tools/epi-suite-estimation-program-interface>.
- [51] Stockholm Convention, "Chemicals Proposed for Listing," 2023. <https://www.pops.int/TheConvention/ThePOPs/ChemicalsProposedforListing/tabid/2510/Default.aspx>.
- [52] H. Ubaid ur Rahman, W. Asghar, W. Nazir, M. A. Sandhu, A. Ahmed, and N. Khalid, "A comprehensive review on chlorpyrifos toxicity with special reference to endocrine disruption: Evidence of mechanisms, exposures and mitigation strategies," Science of the Total Environment, Vol. 755, Article 142649, 2021. [CrossRef]
- [53] D. Mackay, J. P. Giesy, and K. R. Solomon, "Fate in the Environment and Long-Range Atmospheric Transport of the Organophosphorus Insecticide, Chlorpyrifos and Its Oxon," in Ecological Risk Assessment for Chlorpyrifos in Terrestrial and Aquatic Systems in the United States, J. P. Giesy and K. R. Solomon, Eds. Springer Open, pp. 35–76, 2014. [CrossRef]



Research Article

Roles of mobile applications in removing barriers to individual recycling: Case of Türkiye

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ARTICLE INFO

Article history

Received: 20 June 2023

Revised: 22 December 2023

Accepted: 27 December 2023

Key words:

Barriers; Recycling; Recycling apps; Mobile applications; Waste

ABSTRACT

Recycling literature lists barriers that deter individuals from engaging in recycling behavior. These barriers comprise cost-related barriers such as the behavior being challenging, personal barriers such as lack of knowledge or laziness, social barriers such as lack of support from family, believing that others do not recycle, and structural barriers such as hard-to-access recycling bins or lack of incentives. Removing or alleviating these barriers is critical for increasing source separation and recycling rates. In addition to other measures taken, mobile applications (recycling apps) developed to support recycling may also have a significant potential for removing certain barriers. This study aims to evaluate the functions of recycling apps used in Türkiye and highlight their potential to support the behavior through removing the barriers. For this purpose, content analysis of recycling apps was performed. Following the PRISMA protocol, 19 applications were identified and reviewed in detail. The findings revealed ten distinct functions provided by apps. The role of each function in removing specific barriers is evaluated. It was found that recycling apps have huge potential to promote individual recycling by alleviating critical barriers when apps are widely used and their functions consistently meet user expectations. Problems related to some neglected barriers and low usage rates are discussed, and implications of findings are provided.

Cite this article as: Dursun İ, Tümer E, Yürüyen Kılıç H. Roles of mobile applications in removing barriers to individual recycling: Case of Türkiye. Environ Res Tec 2024;7(1)97–107.

INTRODUCTION

Recycling is promoted as a critical approach for reducing waste, alleviating the need for disposal areas, and protecting natural resources. While some countries reached high recycling rates [1] thanks to policies and implemented regulations, some countries, particularly developing countries, still need to increase the low recycling rates [2]. Municipal waste in Türkiye reached 32.3 million tons in 2020, and only 13.2% of it was recycled [3] despite all improvements in waste management legislation, policies, and an

increased number of licensed recycling and recovery facilities. Like other developing countries [4, 5], the low source segregation rates and household waste recycling appear to be significant obstacles to increased recycling rates. It was found that, in different cities in Türkiye, 25–30% of household wastes comprises recyclable solid wastes [6]. So, increasing individual recycling rates appears as a promising approach to reach the targeted 35% recycling rates for 2023 [7] and go beyond it. However, encouraging individuals to change their waste disposal behavior and engage in recycling is challenging.

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This research was conducted within the scope of Project-121K874, supported by TÜBİTAK 1001 - The Scientific and Technological Research Projects Funding Program.



Unlike mixed waste disposal, recycling requires time, place, and effort since consumers must separate and clean the waste, store it for a certain period, and carry or drive it to appropriate recycling bins. On the other hand, in Türkiye, individual recycling has been a voluntary behavior that is not subject to a national-wide incentive program but to some local and temporary rewarding implications. However, the lack of incentive is not the unique barrier to individual recycling. The literature identifies barriers that deter consumers from engaging in individual recycling behavior. Reference [8] provides a literature review on the barrier studies, lists the most prominent barriers, and groups them thematically. The Table 1, which is adapted from [8], shows the most frequently reported barriers in literature. Accordingly, one of the most reported barrier groups is the cost of recycling, referring to the effortful, time-consuming, and economically costly nature of the behavior. Structural barriers comprise the long distances to recycling bins, problems in the waste collection services, and the deficiencies of the policy implementations that support recycling. Personal barriers cover lack of awareness and knowledge regarding why and how to recycle, denying the need for recycling and personal responsibility, suspicions about the recycling system, concerns about storing the waste at home, laziness, and insufficient recyclable waste. Social barriers include unsupportive families and a non-recycling community that consumers live in.

Reference [9] found that Turkish consumers also encounter similar barriers to recycling house waste. Those barriers are likely to directly hinder the behavior or indirectly impair recycling by triggering one other barrier or diluting essential determinants of the recycling behavior (such as personal norms or attitude). For this reason, barriers, especially prominent ones, should be removed or at least alleviated. In this context, mobile applications appear as digital solutions for overcoming some of those barriers and improving recycling behavior.

Mobile applications are software products developed specifically for mobile operating systems installed on handheld devices such as smartphones or tablet computers. Mobile apps are pre-installed on mobile devices or downloaded from various mobile app stores such as Google Play, Apple Store, and iTunes [10]. These applications are free and paid applications in many segments, such as finance, music, education, health, games, entertainment, sports, travel, shopping, books, magazines, and navigation [11]. As in the world, the number of mobile application downloads in Türkiye has gained increasing momentum from year to year. The number of mobile application downloads in Türkiye increased by 8.6 percent from 2021 to 2022, and Turkish users installed mobile applications approximately 5.6 billion times in 2022 [11].

There are some green applications designed to support environmental behaviors such as energy and water saving, eco-friendly mobility, waste reduction, and recycling (See [12] for a review). Recycling applications, among those, are designed to facilitate recycling with functions such as providing content about proper waste classification, reminders

Table 1. Most frequently reported barriers to individual recycling

Cost of recycling
Recycling is effortful
Recycling takes time
Recycling programs are expensive
Structural barriers
Insufficient recycling collection facilities
Unsatisfactory collection services
Mixed collection and disposal issues
Recycle bins are far away
Lack of incentives
State municipalities do not support recycling.
Inadequate legal regulations
Personal barriers
Lack of knowledge about how to recycle
Lack of awareness
Lack of trust in actors in the recycling process
Do not believe in the necessity of individual recycling
The belief is that separated wastes will somehow be mixed again
Denial of responsibility
Concerns about storing waste at home
No place at home for the storage of waste
Lack of recycling habit/routine
Laziness
The insignificant amount of recyclable waste
Social barriers
Lack of family support
Others do not recycle

Source: Adopted from [8].

about recycling, analyzing both the waste impact and the environmental impact of users, conveying current environmental news, and showing the nearest recycling facilities [13]. These functions are provided to encourage recycling by providing convenience, increasing knowledge, and promoting positive attitudes toward recycling.

The recycling literature provides empirical evidence regarding mobile applications' effect on recycling behavior, recycling knowledge, and perceptions. For instance, [14] showed that using a green app increases recycling and indicated that promoting the use of green apps is one remarkable way to increase recycling behavior and enhance recycling knowledge. Besides, [13] emphasized that the intention to use mobile applications has a positive and significant effect on recycling intention, and mobile applications should be used as a tool to get in the habit of recycling. Reference [15] proposed a new recycling mobile application using the RANAS (risks, attitudes, norms, abilities, and self-regulation) approach. In this application, each user tracks their recy-

Table 2. Descriptive information for the apps

App name	Owner type	Geographical scope	Downloads	User reviews	Review score
Waste Log Atık Bildir	Private	No information	500+	–	–
KONYA Sıfır Atık	Local government	Konya	10+	–	–
Bucak Sıfır Atık Projesi	Local government	Burdur-Bucak	100+	–	–
Biriktir-Çevreye Hareket Kat!”	Academia	Türkiye	5.000+	106	3.8
Çevreci Komşu Kart	Local government	Antalya	1.000+	31	4.0
GOP Sıfır Atık	Local government	İstanbul-Gaziosmanpaşa	10.000+	111	4.0
Geri Dönüşüm Noktaları	Local government	İstanbul-Büyükçekmece	500+	12	4.3
AtıkNakit	Local government	İstanbul-Başakşehir	1.000+	39	4.2
Dönüştür Kazan	Local government	İstanbul-Beşiktaş	1.000+	21	4.3
Sultangazi Atıkla Katıl	Local government	İstanbul-Sultangazi	1.000+	8	4.9
Ayrıştır Dönüştür Kazandır	Local government	Adana-Seyhan	100+	–	–
Atık Kazanç	Local government	İstanbul-Zeytinburnu	500+	6	2.8
Şehitkamil Sıfır Atık	Local government	Gaziantep-Şehitkamil	10+	–	–
Bahçelievler Sıfır Atık	Local government	İstanbul-Bahçelievler	100+	–	–
Eyüpsultan Atık Nakit	Private	İstanbul-Eyüpsultan	100+	–	–
Çorlu Sıfır Atık	Private	Tekirdağ-Çorlu	100+	6	3.2
Atık Topla	Local government	İstanbul-Beylikdüzü	100+	–	–
myBiyom-Geri Dönüştür, Kazan	Private	No information	100+	15	3.9
Depozito Bilgi Sistemi	Government	Türkiye	1000+	17	3.4

clable contribution by issuing personal QR code tags. The study results displayed that mobile applications encourage recycling rates to 40% and reduce contamination rates below 2%. Also, [16] revealed that the intention to use mobile apps positively affects recycling intention.

Although empirical evidence is still limited, it is safe to state that recycling applications are promising tools for fostering recycling behavior. But how? Understanding the dynamics of recycling applications' role is critical for designing and managing effective applications. For this reason, app functions and their possible outputs need to be investigated. In this context, this research aims to provide an overview of existing recycling applications (hereafter called recycling apps) used in Türkiye that are designed to promote individual recycling. We specifically focus on uncovering these apps' functions and potential roles in removing well-defined barriers to recycling. The research provides a new perspective on the app-behavior relationship since it is the first study in the literature that examines the effects of apps on barriers to recycling. In addition, the study provides useful insights into the effectiveness and limitations of recycling apps in Türkiye and suggestions on how to improve the apps' promoting impact on recycling behavior.

MATERIALS AND METHODS

For research purposes, a content analysis was conducted on recycling apps. PRISMA protocol (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) was

employed to review the apps. In the identification stage of the protocol, apps were searched in the largest platform for apps, “Google Play Store,” in June 2023 using keywords including “waste,” “recycle,” “recycling,” and “environment.” In the screening stage, apps that are not directly related to recycling were eliminated. In the eligibility stage, apps were evaluated considering the inclusion and exclusion criteria specified. Accordingly, apps that are (1) developed for facilitating or promoting individual recycling in Türkiye (2) currently available for free download were included, while (3) recycling games and (4) apps for the recycling industry were excluded. Following the criteria, 25 applications were downloaded, but 6 were excluded from the study because the content and information about the applications could not be accessed. So, 19 apps were included in the scope of the study. All applications were downloaded by the researchers and analyzed in detail to answer the following questions;

- Which functions do apps provide to facilitate or promote individual recycling?
- Which barriers can be removed through the apps?
- What are the prominent problems or limitations of the apps?

FINDINGS

Table 2 provides descriptive information for the 19 apps, user ratings and download statistics. Accordingly, applications are mostly local and designed for citizens living in a specific district of seven cities in Türkiye. Nine recycling

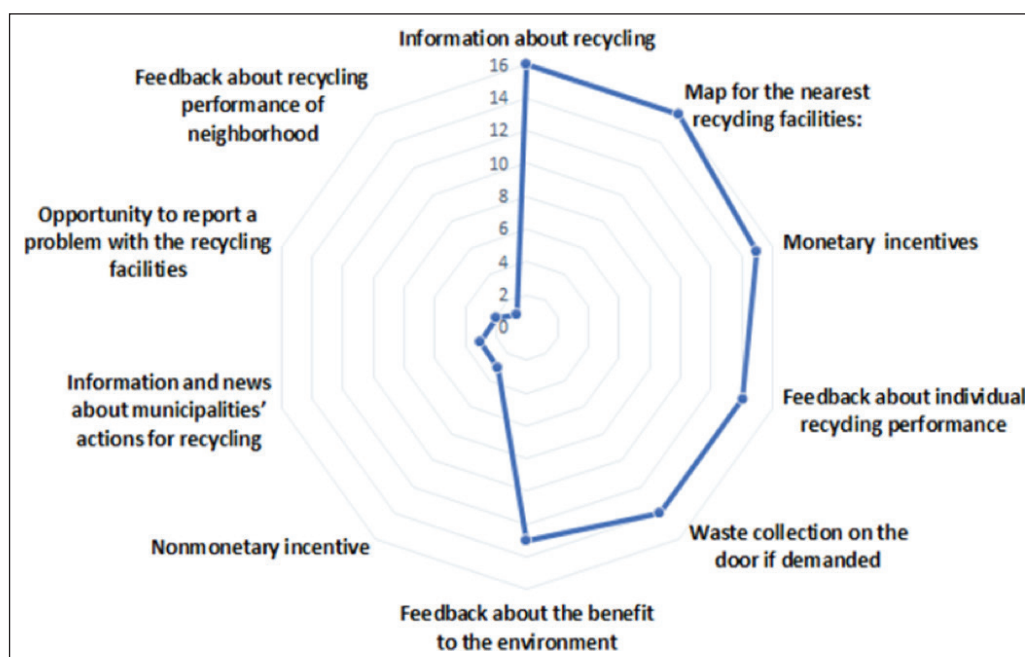


Figure 1. Functions offered by recycling apps.

apps are available for different municipalities of Istanbul, which is the most crowded city in the country, with 18,49% of the population [17]. According to the download statistics, we can generally conclude that applications, except for two, are not yet popular in Türkiye. The "GOP Sıfır Atık" application is the most downloaded, with over 10.000 downloads and 111 reviews. Although GOP is a local application developed for a district of Istanbul, it is remarkable that it has the highest number of downloads. With 5,000+ downloads and 106 reviews, the second most downloaded recycling app is "Biriktir-Çevreye Hareket Kat!" a nationwide app. General low download rates can be attributed to the citizens' low intention to recycle or unawareness of the applications and their functions. Indeed, these applications cover many valuable functions for individual recycling.

The functions offered by the applications to support individual recycling have been examined. It was found that there are ten different functions, and recycling apps cover a combination of those functions. Figure 1 shows how many of the apps offer each function.

Table 3 shows which functions are included in the 19 recycling apps examined. It was observed that 16 apps cover the function of information giving about recycling and maps for the nearest facilities. Besides, 15 apps offer monetary incentives for recycling. 14 of 19 apps give feedback on users' recycling performance and provide an on-demand waste collection on-the-door service. Another prominent function is the function of feedback about the environmental benefits of users' recycling behavior, provided by 14 recycling apps. Nonmonetary incentives, information and news about municipalities' actions for recycling, the opportunity to report a problem with the recycling facilities, and feedback about recycling amount in the neighborhood are rarely covered functions. Examination of barriers to individual recycling

and the functions offered by recycling apps revealed that the functions have a great potential to contribute to the removal of barriers. Table 3 also shows which barriers can be entirely removed or alleviated by the reviewed recycling apps.

DISCUSSION

In line with sustainable development goals, it is an essential but very challenging aim to transform individuals' current lifestyles and habits into a more environmentally friendly and sustainable way. Recycling behavior, which is a voluntary action in Türkiye, is one of the high-cost environmental behaviors that are difficult to develop. Many studies in the literature list the barriers to recycling behavior [18–26]. At this point, digital technologies and information systems help achieve challenging goals and enable behavior change [12]. This study provides a review and content analysis of recycling apps used in Türkiye to give a deeper understanding of the apps' potential to remove the well-accepted barriers and encourage recycling. As summarized in Table 3, each recycling app offers a combination of various functions, and those functions have a significant potential for removing specific barriers to individual recycling. Figure 2 shows which barriers are more often subject to removal by recycling apps.

The Role of Apps in Providing Information

One of the functions offered by almost all applications is the information function. Recycling apps provide information about the purpose of recycling, recyclable materials, or deposits for recyclable materials. Indeed, knowledge and information are investigated as critical antecedents of the behavior in the literature since people can not take action if they do not know the problem or how to solve it. Reference [27], in their meta-analysis comprising 63 empirical studies, reports that it is a well-accepted fact that information

Table 3. Functions provided by each mobile app and barriers removed

App name	Recycling app functions to support individual recycling										Which barriers can be removed through the apps?
	Feedback about individual recycling amount	Feedback about recycling amount in the neighborhood	Feedback about environmental benefits	Waste collection on the door if demanded	Monetary incentive	Nonmonetary incentive	Opportunity to report a problem with the recycling facilities	Directions from the map for the nearest recycling facilities	Information about the purpose of recycling recyclable materials	Information and news about municipalities' actions for recycling	
Waste Log Atık Bildir	✓		✓	✓	✓			✓	✓		1,2,3,4,5,6,7,8,9,11,12,13
KONYA Sıfır Atık		✓		✓				✓	✓	✓	1,2,3,4,5,6,8,9,10,14
Bucak Sıfır Atık Projesi							✓	✓	✓		1,2,3,9,10
Biriktir- Çevreye Hareket Kat!"	✓		✓		✓	✓		✓	✓		1,2,3,7,9,11,12,13
Çevreci Komşu Kart				✓	✓				✓	✓	1,2,3,4,5,6,7,8,10
GOP Sıfır Atık	✓		✓	✓	✓			✓	✓		1,2,3,4,5,6,7,8,9,11,12,13
Geri Dönüşüm Noktaları								✓	✓	✓	1,2,3,9,10
AtıkNakit	✓		✓	✓	✓			✓	✓		1,2,3,4,5,6,7,8,9,11,12,13
Dönüştür Kazan	✓		✓	✓	✓			✓	✓		1,2,3,4,5,6,7,8,9,11,12,13
Sultangazi Atıkla Katıl	✓		✓	✓	✓			✓	✓		1,2,3,4,5,6,7,8,9,11,12,13
Ayrıştır Dönüştür Kazandır	✓		✓	✓	✓			✓	✓		1,2,3,4,5,6,7,8,9,11,12,13
Atık Kazanç	✓		✓		✓			✓			1,2,3,7,11,12,13
Şehitkamil Sıfır Atık	✓		✓	✓	✓			✓	✓		1,2,3,4,5,6,7,8,9,11,12,13
Bahçelievler Sıfır Atık	✓		✓	✓	✓			✓	✓		1,2,3,4,5,6,7,8,9,11,12,13
Eyüpsultan Atık Nakit	✓		✓	✓	✓			✓	✓		1,2,3,4,5,6,7,8,9,11,12,13
Çorlu Sıfır Atık	✓		✓	✓	✓			✓	✓		1,2,3,4,5,6,7,8,9,11,12,13
Atık Topla				✓					✓		1,2,3,4,5,6,8,9
myBiyomGeri Dönüştür; Kazan	✓		✓	✓	✓	✓			✓		1,2,3,4,5,6,7,8,9,11,12,13
Depozito Bilgi Sistemi	✓				✓	✓	✓	✓	✓		1,2,3,7,9,10,13
1. Recycling is effortful										8. State municipalities do not support recycling-	
2. Recycling takes time										9. Lack of knowledge	
3. Insufficient recycling collection facilities										10. Lack of trust in actors in the recycling process	
4. Unsatisfactory collection services										11. Do not believe in the necessity of individual recycling	
5. Mixed collection and disposal issues										12. Laziness	
6. Recycle bins are far away.										13. The insignificant amount of recyclable waste	
7. Lack of incentives										14. Others do not recycle	

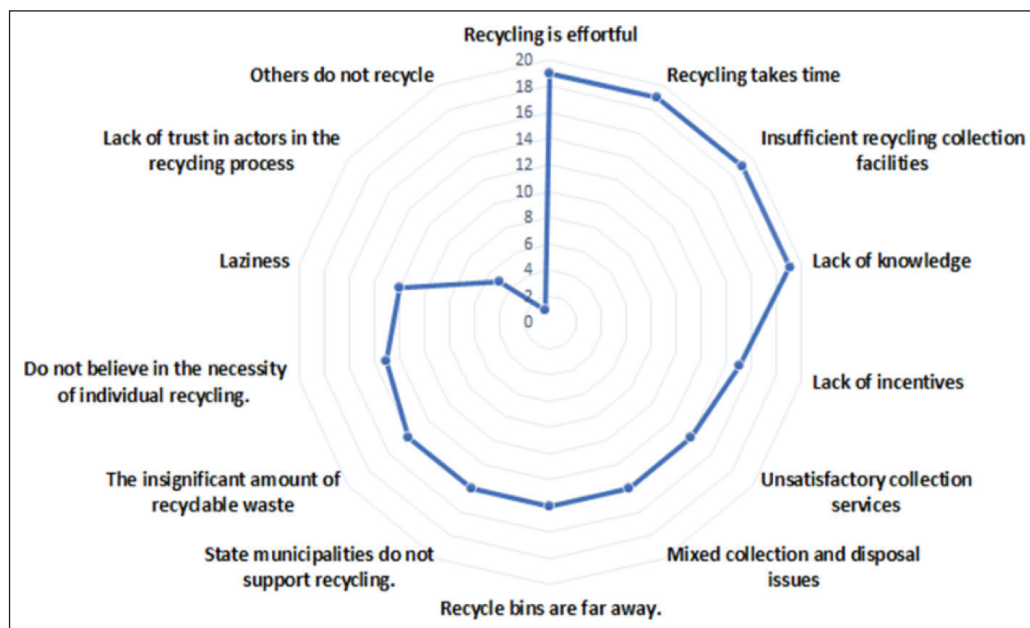


Figure 2. Barriers that can be removed or alleviated by recycling apps.

has a positive and significant correlation with recycling behavior. From the opposite perspective, “lack of knowledge” on what, why, and how to recycle is among the most common barriers to individual recycling in the literature [e.g., 28–30]. Information provided by the apps helps to remove the “lack of knowledge” barrier since users get a deeper understanding of the purpose and positive outputs of individual recycling, identify recyclable materials clearly, and learn how to recycle appropriately. App-provided information is more likely to promote behaviors than conventional communication campaigns since app users are a specific target group already interested in and intent on recycling. However, there is room for functional development for apps through tailoring the information according to the needs of the user. As stated by [31] information tailored according to the characteristics and needs of a specific target group will be more effective in promoting the behavior. However, apps provide generic information for all users. To increase the effectiveness of the recycling apps, they can customize the information provided to users after discovering their primary intentions, beliefs, and needs for recycling. Besides, new ways of information giving can be employed. For instance, an interactive training module customized for specific user segments can be more effective for recycling education. Short video content can also be beneficial in demonstrating visually how recyclable waste should be separated and stored. Furthermore, if videos feature reliable celebrities or opinion leaders, videos not only give information about recycling but also inspiration for recycling.

Some recycling apps also regularly inform users about municipalities' investments, activities, events, waste management, and recycling achievements. In this way, apps may help overcome the barrier of distrust in the recycling actors about the proper collection, care of, and management of recyclables [24, 32]. The removal of this barrier is crucial

since the feeling of distrust in recycling actors makes recycling a meaningless action for consumers.

Finally, two applications were found to enable reverse information flow from users to app owners through the reporting function. The function allows users to inform the authorities about the problems in recycling facilities. Although the reporting function is not directly related to the behavior, it may still provide distal support for recycling because contributing to the solution of the problem may increase users' involvement in recycling. More importantly, a quick solution to the reported problem can strengthen participants' trust in the system and alleviate the “lack of trust in actors in the recycling process.”

The Role of Apps in Providing Feedback

Providing feedback about individual recycling performance is another function of recycling apps. Users are given statistics about the amount of material they collect for a period. Thanks to this function, users can see that recyclable wastes, even low in quantity, create significant waste when collected after a certain period. So, the function may alleviate the barrier of “the insignificant amount of recyclable waste” [28, 33, 34]. This barrier appears when consumers argue that they produce a minimal amount of recyclables and yields to the belief that recycling is unnecessary. More importantly, feedback about users' recycling performance may promote their perceived behavioral control, which refers to the conviction that they have the ability to recycle their waste. The Theory of Planned Behavior [35] indicates that perceived behavioral control increases recycling both directly and indirectly. Furthermore, by adding a new function to the apps, users can be given the opportunity to set daily, weekly, or monthly recycling goals; notifications can be sent to encourage users to achieve these goals and give feedback about their final achievement.

Not only the amount of materials collected, but apps also give feedback about the environmental benefits of users' recycling efforts. Through this function, users are informed about how much environmental benefit their recycling efforts achieve. The benefit is usually expressed in statistics indicating the reduction in carbon emissions or carbon footprint. Particular apps also provide statistics regarding saved trees, energy, petrol, raw material, and disposal areas depending on the amount of recycled material. This function will likely remove the "do not believe in the necessity of individual recycling" barrier by providing diagnostic information about the benefits of individual recycling efforts. Besides, the function helps consumers to understand their contribution to saving the environment through their recycling efforts. This feedback may be an internal motivator for users with strong environmental value to sustain their recycling efforts. Even it can have a stronger impact than incentives, as [36] indicated. For this reason, feedback on environmental benefits may also help users overcome their "laziness" and take action.

Besides, a certain app gives feedback about the recycling performance of the neighborhood. This additional function helps users track recycling performance in their area (e.g., their street, neighborhood, and city) from the cumulative amount of material that was collected in the area. This function is promising for overcoming the "others do not recycle" barrier since the user will see how much material others recycle. The belief that "others do not recycle" may hinder the behavior in two ways. First, consumers may worry about feeling shame for being one of the few people in a community who recycle [37]. The function helps to observe others' recycling efforts and normalize recycling as a waste disposal behavior. This feedback shows that a significant number of people are recycling in a neighborhood. In this way, recycling transforms into a mutually agreed action [37], which helps to create subjective norms that the Theory of Planned Behavior considers an essential determinant of behavior [35]. Second, the belief that "others do not recycle" may fuel helplessness, referring to the fact that consumers can not solve a problem alone with individual effort. So, realizing the collaborative effort for recycling through feedback from the app is likely to motivate the users to take future actions. Unfortunately, this function is provided by only one of 19 recycling apps. To overcome the feeling of helplessness and build a social norm, consumers should see how much "others" recycle. So, this function is a must for all applications, especially in Türkiye, where recycling is a behavior that has not yet become widespread.

The Role of Apps in Reducing the Cost of Recycling

Long distance to the recycling bins is a prominent structural barrier often listed in individual recycling research [18, 32, 34, 38–42]. The distance increases the cost of recycling since it will increase the effort, time, and sometimes money that recycling requires. One of the most prominent functions of recycling apps is maps for the nearest recycling facilities. Users can see the location of recycling bins for different materials on these maps. Although app-pro-

vided maps can not reduce the distance to the bins, they help users find the nearest facility more easily and minimize search efforts. In this way, apps will at least help reduce the negative impact of the "recycling is effortful" and "recycling takes time" barriers, if not eliminate them entirely. Besides, these maps will help users recognize the number of bins located for recycling and alleviate the perception of "insufficient recycling collection facilities."

To increase the effectiveness of the apps, the map function can be upgraded by expanding the coverage with markets, stores, schools, or other public buildings that provide recycling bins. In this way, the perception of accessibility will increase substantially. Moreover, apps may inform users through notifications when a new recycling point is added to their area. This way, users can take advantage of the new facility and contribute to their community's recycling efforts.

In addition to the provided maps, apps mostly provide an on-door waste collection service. This function has a vast potential to remove critical structural barriers such as distance to recycling bins, insufficient recycling collection facilities, and unsatisfactory collection services. Besides, the function reduces the perception of "recycling is effortful" or "recycling takes time" since users do not have to take recyclable materials to recycle bins. If the owner of the app is the municipality, the function may also alleviate the perception that "municipalities do not support recycling." The function of on-door waste collection appears to be a sure way to motivate the behavior. However, to prevent unintended ecological harms, it will be helpful to remind users that when an on-door waste collection service is used, it increases the use of garbage collection vehicles, which in turn increases road traffic, fuel consumption, air pollution, and emissions.

In addition to the maps and online collection service, a new function can be suggested for recycling apps to reduce the cost of recycling indirectly by helping new starters to get a recycling routine, the lack of which is indicated as a barrier to behavior [34, 43, 44]. Obviously, if consumers do not have a recycling habit, it is not easy to remember their daily tasks. Recycling apps can remind users to act consistently by sending notifications. Moreover, apps may remind users to take recyclables out on waste collection days (if there are any) or deliver waste to recycling facilities. This function may help users engage recycling in their daily routines more quickly as a new waste disposal behavior.

The Role of Apps in Motivating Recycling

Another popular function of recycling apps is providing incentives for recycling. Incentives are some tangible and desirable consequence (e.g., money, privilege) that individuals receive on emitting some observable and verifiable behavior, and they are used all around the world to promote desirable behaviors [45]. Recycling apps use monetary incentives to increase the benefit/cost ratio to make the behavior more profitable for the individual and encourage the behavior [46]. Apps provide monetary incentives by allowing users to earn money, crypto money, gifts, coupons, and discounts

in proportion to the recycling they make. Satisfactory monetary incentives offered by the app can directly remove the barrier of “lack of incentives” and support behavior by decreasing the cost/benefit ratio of the recycling behaviors.

At this point, new kinds of incentives can be suggested to mitigate users’ “concerns about waste storage at home,” which is a barrier that apps neglect. This barrier reflects concerns that storing recyclable materials at home may cause a mess, clutter, odors, or health problems [18, 28, 47, 48]. Among the incentives provided for recycling performances, it would be beneficial to include recycling-related gifts such as aesthetic recycling bins or bags, allowing easier, neater, and safer storage of recyclable wastes at home.

Apart from monetary incentives, some apps also offer non-monetary incentives that cover the opportunities to donate to various charities in proportion to the amount of recycling. This function removes the “lack of incentives” barriers for the users who are not motivated through monetary incentives. Apps may provide some additional social incentives, such as scoring and reward systems that encourage users to recycle more. Besides, apps may offer social share buttons to allow users to share their recycling and environmental achievements with their friends and followers, which can significantly motivate the users and their social media community. Additionally, app-social media integration enables the organization of recycling-related challenges and events through which users can be encouraged to participate and make a difference in the environment and society.

Problems with Recycling Apps

In general, this research revealed that existing recycling applications provide solutions to the most reported barriers stemming from the effortful and time-consuming nature of recycling, lack of knowledge, dissatisfaction with waste collection services, and lack of incentives, to some extent. However, we must note that these optimistic inferences about the functions’ potential are based on the assumption that functions operate effectively and apps are used widely. Functions that cannot steadily meet the users’ expectations are likely to hinder the users’ trust in the application, the owner of the application, and the recycling systems, which will, in turn, reduce motivation for the behavior. In other words, apps created for barrier removal are likely to be a barrier to the behavior if their functions fail to operate consistently.

Another condition for removing the barriers through apps is that the apps should be accessed and used by a wide range of users. However, recycling apps, which are reasonably local, are limited in number. This finding indicates that millions of potential users living in many regions, cities, or districts in Türkiye have no access to a recycling app. Considering the possible contributions of applications, developing new local applications for individuals living in different regions of the country is critical. Although it is more difficult to process, the widespread use of nationwide applications will provide a similar benefit. At this point, another problem draws attention, which is that the existing apps are not widely used. The

most frequently downloaded app has slightly more than ten thousand users. This finding shows that many people, even those interested in recycling, need to be made aware of the apps active in their region. It is critical to inform potential users about applications with communication and promotional campaigns since recycling apps will only be effective if people widely use them.

Moreover, it is critical that an application is easy to use, that individuals perceive it as useful, and that they have a generally positive attitude toward it [14]. However, when the apps’ ease of use is examined within the study, it was observed that some applications require lots of very detailed personal information when logging in. This feature of applications is likely to discourage users who are interested in recycling but still need to have a strong motivation to start using the application. For this reason, it will be beneficial to make certain functions available without giving detailed address information in all applications. In this way, users may learn about the benefits of recycling, recyclable materials, the incentive system provided by the application, recycling bins in a certain region, and available door-to-door collection services. In this way, apps can motivate users to start recycling efforts. Finally, the interfaces of some recycling apps are not easily understood, and designs could be more creative and remarkable.

CONCLUSION

This research examines 19 mobile applications (local or nationwide) developed to support recycling behavior in Türkiye. The findings showed that there are ten different functions available in these applications. Although some of them cover different ranges of functions, recycling applications are mainly similar. These applications have great potential to remove the main barriers and increase individual recycling rates. Particularly, apps remove a well-accepted barrier called “lack of knowledge” through the function of providing information about recycling and alleviate the barrier of “lack of trust in actors in the recycling process” by informing users about municipalities’ recycling actions. Another popular app function is providing feedback about users’ recycling performance that hinders the obstructive belief of “producing an insignificant amount of recyclable waste.” Through the function of giving feedback about the environmental benefits of users’ recycling efforts, the barriers of “denying the necessity of individual recycling” and “laziness” may be overcome. More importantly, the function of providing feedback about the recycling performance of the neighborhood has enormous potential to dilute the “others do not recycle” barrier, which is found to be demotivating. Furthermore, apps help decrease “recycling costs” by providing maps showing the nearest recycling facilities and enabling collection on the door if demanded. Through these functions, the behavior-impeding beliefs of “recycling is effortful,” “recycling takes time,” and “recycling collection facilities are insufficient” can be diminished. Finally, apps also have a significant potential

to promote recycling behavior by providing monetary and nonmonetary incentives for emitting recycling. The findings also showed that recycling apps can be improved by adding the aforementioned new functions that will increase the behavioral impact of the apps.

However, recycling apps have a critical problem: Local applications are available in a very limited number of regions in Türkiye. On the other hand, the number of users in the regions where the recycling app is available is very low. To unlock the barrier removal potential of the apps, it is necessary to increase the number of local applications with an easy-to-use design and promote the apps to attract potential users.

The essential prerequisite for the success of these applications, even those that are well-designed and widely used, is that the functions consistently meet the users' expectations. On the contrary, applications will be a new barrier instead of facilitating the behaviors. Future studies are needed that will be conducted in regions where recycling apps are available and will examine the main motivations and challenges in using these apps, users' satisfaction with the functions offered, and the effects of the functions on behavior.

When evaluating research findings and implications, some limitations should be considered. First, this research only focuses on apps available in "The Google Play Store." So, the study did not consider recycling apps that the store does not cover. For this reason, distinct recycling apps that provide different functions may have been overlooked. Besides, the download statistics of the reviewed recycling apps only show the number of downloads in the specified store and may actually be higher. Another limitation is that apps were evaluated based on researchers' short-term experience with applications. For this reason, some specific strengths and/or weaknesses of the apps that appear in the long run may be missed. Studies based on more extended application usage may make more robust conclusions about the advantages and limitations of the applications.

DATA AVAILABILITY STATEMENT

The author confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

FUNDING STATEMENT

This research was conducted within the scope of Project-121K874, supported by TÜBİTAK 1001 - The Scientific and Technological Research Projects Funding Program.

REFERENCES

- [1] Eurostat, "Waste statistics," 2022. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Waste_statistics#Total_waste_generation.
- [2] S. Haghighatjoo, R. Tahmasebi, and A. Noroozi, "Application of community-based social marketing (CBSM) to increase recycling behavior (RB) in primary schools," *Social Marketing Quarterly*, Vol. 26(4), pp. 297–308, 2020. [CrossRef]
- [3] Turkish Statistical Institute (TURKSTAT), "Atik İstatistikleri 2020," 2020. <https://data.tuik.gov.tr/Bulten/Index?p=Atik-Istatistikleri-2020-37198>.
- [4] M. Banga, "Household knowledge, attitudes and practices in solid waste segregation and recycling: the case of urban Kampala," *Zambia Social Science Journal*, Vol. 2(1), pp. 4, 2011.
- [5] T. A. Otitoju and L. Seng, "Municipal solid waste management: household waste segregation in Kuching South City, Sarawak, Malaysia," *American Journal of Engineering Research*, Vol. 3(6), pp. 82–91, 2014.
- [6] E. Metin, A. Eröztürk, and C. Neyim, "Solid waste management practices and review of recovery and recycling operations in Turkey," *Waste Management*, Vol. 23(5), pp. 425–432, 2003. [CrossRef]
- [7] MofEUCC, "T.C. Ministry of Environment, Urbanisation and Climate Change," 2017.
- [8] E. Tumer Kabadayı, İ. Dursun, C. Gökmen Köksal, A. Durmaz, and M. Yüksel, "Bireysel geri dönüşüm davranışı önündeki engeller üzerine sistematik literatür taraması," *International Journal of Eurasia Social Sciences*, Vol. 14(52), pp. 800–835, 2023.
- [9] M. Ö. Umut and M. N. Velioglu, "Sosyal pazarlamada hedef kitlenin derinlemesine analizi ile geri dönüşüm davranışını haritalamak," *Pazarlama Teorisi ve Uygulamaları Dergisi*, Vol. 2(1), pp. 1–20, 2016.
- [10] H. Hoehle, and V. Venkatesh, "Mobile application usability," *MIS Quarterly*, Vol. 39(2), pp. 435–472, 2015. [CrossRef]
- [11] Statista, "App downloads in Turkey," 2022. <https://www.statista.com/statistics/1375234/turkey-app-downloads/>.
- [12] B. Brauer, C. Ebermann, B. Hildebrandt, G. Remané, and L. M. Kolbe, "Green by app: The contribution of mobile applications to environmental sustainability," in *Proceedings of 20th Pacific Asia Conference on Information Systems (PACIS 2016)*, Chiayi, Taiwan, 2016.
- [13] M. Sozoniuk, J. Park, and N. Lumby, "Investigating residents' acceptance of mobile apps for household recycling: A case study of New Jersey," *Sustainability*, vol. 14(17), Article 10874, 2022. [CrossRef]
- [14] K. K. De Wildt, and M. H. Meijers, "Time spent on separating waste is never wasted: Fostering people's recycling behavior through the use of a mobile application," *Computers in Human Behavior*, Vol. 139, Article 107541, 2023. [CrossRef]

- [15] X. Shan, W. L. Ang, and E. H. Yang, "Mobile app-aided risks, attitudes, norms, abilities and self-regulation (RANAS) approach for recycling behavioral change in Singapore," *Resources, Conservation and Recycling*, Vol. 162, Article 105049, 2020. [\[CrossRef\]](#)
- [16] E. Juaneda-Ayensa, M. Clavel San Emeterio, S. Ciriolo-Jordan, and L. González-Menorca, "Unified theory of acceptance and use of social apps: (UTAU-SA): The role of technology in the promotion of recycling behavior," *International Scientific Conference on Innovations in Digital Economy*, pp. 3–22, Cham: Springer International Publishing, 2020. [\[CrossRef\]](#)
- [17] Goİ-Governship of İstanbul, "Nüfus bakimindan Türkiye'nin en büyük kenti İstanbul," 2023. <http://www.istanbul.gov.tr/nufus-bakimindan-turkiyenin-en-buyuk-kenti-istanbul>. Accessed on June 14, 2023.
- [18] I. S. Zen, Z. Z. Noor, and R. O. Yusuf, "The profiles of household solid waste recyclers and non-recyclers in Kuala Lumpur, Malaysia," *Habitat International*, Vol. 42, pp. 83–89, 2014. [\[CrossRef\]](#)
- [19] P. Mtutu, and G. Thondhlana, "Encouraging pro-environmental behavior: Energy use and recycling at Rhodes University, South Africa," *Habitat International*, Vol. 53, pp. 142–150, 2016. [\[CrossRef\]](#)
- [20] B. R. Dlamini, I. T. Rampedi, and A. P. Ifegbesan, "Community resident's opinions and perceptions on the effectiveness of waste management and recycling potential in the Umkhanyakude and Zululand District Municipalities in the KwaZulu-Natal Province of South Africa," *Sustainability*, Vol. 9(10), Article 1835, 2017. [\[CrossRef\]](#)
- [21] L. S. Conke, "Barriers to waste recycling development: Evidence from Brazil," *Resources, Conservation and Recycling*, Vol. 134, pp. 129–135, 2018. [\[CrossRef\]](#)
- [22] A. Almasi, M. Mohammadi, A. Azizi, Z. Berizi, K. Shamsi, A. Shahbazi, and S. A. Mosavi, "Assessing the knowledge, attitude and practice of the Kermanshah women towards reducing, recycling and reusing of municipal solid waste," *Resources, Conservation and Recycling*, Vol. 141, pp. 329–338, 2019. [\[CrossRef\]](#)
- [23] C. Denner, and J. Vermaas, "Assessment of barriers preventing recycling practices among bars and eateries in central South Africa," in A. Ortega Riejos, M. Lega, and H. Itoh, (Eds.), *Waste Management and the Environment*, Vol. IX, pp. 183, 2019. [\[CrossRef\]](#)
- [24] E. Drimili, R. Herrero-Martin, J. Suardiaz-Muro, and E. Zervas, "Public views and attitudes about municipal waste management: Empirical evidence from Athens, Greece," *Waste Management & Research*, Vol. 38(6), pp. 614–625, 2020. [\[CrossRef\]](#)
- [25] M. Hao, D. Zhang, and S. Morse, "Waste separation behavior of college students under a mandatory policy in China: A case study of Zhengzhou City," *International Journal of Environmental Research and Public Health*, Vol. 17(21), Article 8190, 2020. [\[CrossRef\]](#)
- [26] K. W. M. Siu, and J. X. Xiao, "Public facility design for sustainability: Participatory action research on household recycling in Hong Kong," *Action Research*, Vol. 18(4), pp. 448–468, 2020. [\[CrossRef\]](#)
- [27] S. Miafodzyeva, and N. Brandt, "Recycling behaviour among householders: Synthesizing determinants via a meta-analysis," *Waste and Biomass Valorization*, Vol. 4, pp. 221–235, 2013. [\[CrossRef\]](#)
- [28] Y. Moh, and L. A. Manaf, "Solid waste management transformation and future challenges of source separation and recycling practice in Malaysia," *Resources, Conservation and Recycling*, Vol. 116, pp. 1–14, 2017. [\[CrossRef\]](#)
- [29] H. Wang, X. Liu, N. Wagner, K. Zhang, F. Wang, S. Zhang, et al., "Key factors influencing public awareness of household solid waste recycling in urban areas of China: A case study," *Resources, Conservation and Recycling*, Vol. 158, Article 104813, 2020. [\[CrossRef\]](#)
- [30] F. T. Seik, "Recycling of domestic waste: early experiences in Singapore," *Habitat International*, Vol. 21(3), pp. 277–289, 1997. [\[CrossRef\]](#)
- [31] M. W. Kreuter, D. Farrell, L. Olevitch, and L. Brennan, "Tailored health messages: Customizing communication with computer technology," Mahwah, Erlbaum, 1999. [\[CrossRef\]](#)
- [32] M. Ojala, "Recycling and ambivalence: Quantitative and qualitative analyses of household recycling among young adults," *Environment and Behavior*, Vol. 40(6), pp. 777–797, 2008. [\[CrossRef\]](#)
- [33] S. S. Chung, and C. S. Poon, "Recycling behavior and attitude: The case of the Hong Kong people and commercial and household wastes," *The International Journal of Sustainable Development & World Ecology*, Vol. 1(2), pp. 130–145, 1994. [\[CrossRef\]](#)
- [34] C. Knussen, and F. Yule, "I'm not in the habit of recycling: The role of habitual behavior in the disposal of household waste," *Environment and Behavior*, Vol. 40(5), pp. 683–702, 2008. [\[CrossRef\]](#)
- [35] Ajzen, "The theory of planned behavior," *Organizational Behavior and Human Decision Processes*, Vol. 50, pp. 179–211, 1991. [\[CrossRef\]](#)
- [36] E. S. Iyer, and R. K. Kashyap, "Consumer recycling: Role of incentives, information, and social class," *Journal of Consumer Behaviour: An International Research Review*, Vol. 6(1), pp. 32–47, 2007. [\[CrossRef\]](#)
- [37] R. De Young, "Exploring the difference between recyclers and non-recyclers: The role of information," *Journal of Environmental Systems*, Vol. 18(4), pp. 341–351, 1988. [\[CrossRef\]](#)
- [38] G. Kok, and S. Siero, "Tin recycling: Awareness, comprehension, attitude, intention, and behavior," *Journal of Economic Psychology*, Vol. 6(2), pp. 157–173, 1985. [\[CrossRef\]](#)
- [39] D. Perrin, and J. Barton, "Issues associated with transforming household attitudes and opinions into materials recovery: A review of two kerbside recycling schemes," *Resources, Conservation and Recycling*, Vol. 33(1), pp. 61–74, 2001. [\[CrossRef\]](#)
- [40] J. D. M. Saphores, and H. Nixon, "How effective are current household recycling policies? Results from

- a national survey of US households,” *Resources, Conservation and Recycling*, Vol. 92, pp. 1–10, 2014. [\[CrossRef\]](#)
- [41] A. Babaei, N. Alavi, G. Goudarzi, P. Teymouri, K. Ahmadi, and M. Rafiee, “Household recycling knowledge, attitudes and practices towards solid waste management,” *Resources, Conservation and Recycling*, Vol. 102, pp. 94–100, 2015. [\[CrossRef\]](#)
- [42] J. T. S. Pedersen, and H. Manhice, “The hidden dynamics of household waste separation: An anthropological analysis of user commitment, barriers, and the gaps between a waste system and its users,” *Journal of Cleaner Production*, Vol. 242, Article 116285, 2020. [\[CrossRef\]](#)
- [43] J. Jesson, “Household waste recycling behavior: A market segmentation model,” *Social Marketing Quarterly*, Vol. 15(2), pp. 25–38, 2009. [\[CrossRef\]](#)
- [44] M. Ö. Umut, and M. N. Velioglu, “Sosyal pazarlamada hedef kitlenin derinlemesine analizi ile geri dönüşüm davranışını haritalamak,” *Journal of Theory and Practice in Marketing*, Vol. 2(1), pp. 1–20, 2016.
- [45] K. Silverman, B. P. Jarvis, J. Jessel, and A. A. Lopez, “Incentives and motivation,” *Translational Issues in Psychological Science*, Vol. 2(2), Article 97, 2016. [\[CrossRef\]](#)
- [46] J. Thøgersen, “Monetary incentives and recycling: Behavioural and psychological reactions to a performance-dependent garbage fee,” *Journal of Consumer Policy*, Vol. 26(2), pp. 197–228, 2003. [\[CrossRef\]](#)
- [47] J. Vining, N. Linn, and R. J. Burdge, “Why recycle? A comparison of recycling motivations in four communities,” *Environmental Management*, Vol. 16(6), pp. 785–797, 1992. [\[CrossRef\]](#)
- [48] Pegels, J. L. Castañeda, C. Humphreys, C. Kötter, M. Negre, C. Weidner, and F. Kutzner, “Aligning recycling behaviors and the recycling system—Towards a full cycle of materials and behavioral methods,” *Waste Management*, Vol. 138, pp. 1–7, 2022. [\[CrossRef\]](#)



Research Article

Effect of purification methods on the quality and morphology of plastic waste-derived carbon nanotubes

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ARTICLE INFO

Article history

Received: 30 May 2023

Revised: 07 January 2024

Accepted: 13 January 2024

Key words:

Plastic waste derived carbon nanotubes; Purification methods; Chemical oxidation; Air oxidation; Morphology; Quality

ABSTRACT

Recent innovative research efforts on the usage of plastic wastes as a cheap carbon source for carbon nanotubes (CNTs) production have emerged as a low-cost and sustainable means of producing CNTs. However, plastic waste-derived CNTs are rarely used in some purity-sensitive and high-alignment needed applications due to the poor quality of CNTs resulting from the abundance of impurities such as non-crystalline amorphous carbon, metallic nanoparticles, and other impurities. Therefore, purification is a crucial issue to be addressed to fully harness all potential applications of CNTs derived from waste plastic materials. Here, the effect of employing different purification methods on the morphology and purity of waste plastic-derived CNTs was investigated. CNTs were synthesized using waste polypropylene plastic as carbon feedstock via a single-stage catalytic chemical vapour deposition (CVD) technique. As-produced CNTs were purified using liquid-phase oxidation (chemical oxidation in nitric acid), gas-phase oxidation in air, and a combination of both liquid- and gas-phase oxidation methods. The synthesized and purified CNTs were characterized for morphology, purity, surface functional groups, thermal stability, and crystallinity using Transmission electron microscopy (TEM), Raman spectroscopy, Fourier Transform Infrared spectroscopy (FTIR), Thermogravimetric analysis (TGA), and X-ray diffraction (XRD), respectively. Results obtained showed that a combination of both liquid and gas phase oxidation purification techniques resulted in purer, better quality, and less defective CNTs with an IG'/IG value of 0.89 and ID/IG value of 0.86, while chemically treated CNTs (CNT-PC) presented more structurally defective CNTs and shortened nanotubes compared to other investigated treatment methods with an ID/IG value of 0.96. CNTs purified by a multi-step protocol (CNT-PAC) showed the highest weight loss of 72.3% indicating the highest quality and the presence of filamentous carbon. This study confirms that the choice of purification techniques influences the morphology and quality of plastic-derived CNTs.

Cite this article as: Modekwe H, Ramatsa I. Effect of purification methods on the quality and morphology of plastic waste-derived carbon nanotubes. Environ Res Tec 2024;7(1)108–117.

INTRODUCTION

Carbon nanotubes (CNTs) are a one-dimensional (1D) allotropic form of carbon whose diameter exists in the nanometer and its length in micrometer scale [1, 2]. CNTs consist of mainly three types namely: single-walled (SWCNTs),

double-walled (DWCNTs), and multi-walled (MWCNTs). These materials possess extraordinary physicochemical properties, including high mechanical strength, excellent optical, thermal stability, and electrical conductivity properties, as well as large surface area, high aspect ratio, etc. The versatile potential applications of CNTs as functional

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materials in various fields of science, engineering, medicine, manufacturing, electronics, construction, etc. [3] have accelerated the global CNTs production capacity from 400–460 tons in 2013 [4] and are forecasted to reach 7000 tons by 2025 [5]. In 2019, the global CNTs market value was about \$670.5 million, with a compound annual growth rate (CAGR) of about 34% [6, 7]. Some of the existing applications of CNTs are in hydrogen storage, reinforcement materials in high-strength composites and polymers, drug delivery and tissue engineering, water purification, CO₂ capture and storage, energy storage and conversion, catalysis, sensors, etc. [1, 2]. In 2019, CNTs accounted for the highest market share of 26.9% in energy-related nanomaterials [8].

The different methods used in the synthesis of CNTs are laser ablation, chemical vapour deposition, and electric-arc discharge [1]. Depending on the method of CNTs' production, CNTs are usually prepared using carbonaceous materials as the sources of carbon and in the presence of heat. In addition, metallic catalysts are usually incorporated during the synthesis process to improve the product yield and also catalyze the breakdown of hydrocarbon molecules, thereby reducing the temperature gradient and the reaction rate, which impact the energy requirement and cost (by indirectly reducing the cost of production) [9]. Depending on the synthesis technique employed, the nanotube powder produced contains a considerable number of other impurities, ranging from residual unreacted metal catalysts, amorphous carbon, nanocrystalline graphite, fullerenes, and other unwanted materials. The presence of these impurities reduces CNTs' performance and potential applications in various fields [10, 11].

Also, heterogenous catalysts used in CNTs growth are embedded in various metal oxides as catalyst supports to achieve desired active metal stability, improve active metal dispersion, minimize agglomeration, and assist in obtaining good and small active metal particle sizes [12]. These supports are very hard to remove, and using certain harsh purification treatment methods destroys the structural integrity of the nanotubes and restricts their performance in certain real-life applications [13].

The production and consumption of plastic materials have continued to increase over the years due to the increasing population as well as high demand from household and industrial applications [14]. In 2018, global plastic production reached 360 million tonnes [15]. According to the report by Geyer et al. [16], as little as 9% of the global plastic waste is recycled, 19% is incinerated, and 22% of this generated waste is mismanaged and unaccounted for, while a larger percentage (50%) of generated plastic wastes is discarded in landfills [16]. Plastics account for over 75% of the total marine litter [17], and it was estimated in 2010 that about 4.8–12.7 million metric tonnes of plastic entering the ocean each year are mostly from land-based sources [17].

Waste plastics are composed of very high carbon content; the use of plastic wastes as cheap feedstock in the synthesis of CNTs has the potential to replace the commonly used high-purity light-weight hydrocarbon materials such as

methane, acetylene, benzene, etc., which have other important industrial uses. However, due to the complex nature of plastics, utilizing them as feedstock in CNTs production results in the formation of more complicated and complex structures and unreacted carbon together with other nanomaterials (such as fullerenes, nanofibers, nano-onions, graphite, nanosheets, and so on). Therefore, apart from the usual unreacted metal catalysts, enormous quantities of amorphous carbons are expected as impurities and need to be removed from plastic waste-derived CNTs. Hence, choosing a particular treatment method that will remove all or considerable quantities of impurities present in plastic-derived CNTs without damaging the original length and structural integrity of CNTs is more of a difficult task.

The major purification methods are grouped into chemical and physical methods [18]. In using the chemical oxidation purification techniques, CNTs purification is based on the principle that metallic nanoparticles dissolve easily in acids or bases, while gas-phase oxidation treatment is also based on the fact that carbonaceous impurities oxidize at a faster rate than CNTs [19]. Purification by chemical treatment presents defects on the nanotubes' wall surface and results in a pentagonal structure on the nanotubes' ends, resulting in the loss of a considerable amount of CNTs with a deformed structure and morphology of the nanotubes [19].

Common oxidative treatment methods are gas-phase oxidation (using oxidants such as air, steam, etc. at an oxidation temperature range of 225 to 760 °C; this method is usually employed to remove molecules adsorbed inside the matrices of CNTs and oxidize thermally unstable non-crystalline carbon). A study by Boncel and Kozol [20] utilized thermal treatment in argon for the removal of encapsulated iron metal in MWCNTs. Clancy et al. [21] conducted a comparison study on several purification routes (acid treatment (HNO₃, HCl, H₂O₂/HCl), gas-phase (air oxidation, water vapour), electrochemical reduction and reduction with NaNP/DMAc (using sodium naphthalide in dimethylacetamide) for purifying commercial SWCNTs type (Tuball™). According to their study, SWCNTs purification by air oxidation does not result in functionalization of the tubes, and amorphous carbon was significantly reduced. However, the technique was not efficient in metal catalyst removal.

Other oxidative treatment methods such as liquid-phase oxidation (which involves treatment with oxidizing agents and mineral acids such as KMnO₄, H₂O₂, HNO₃, H₂SO₄, or their mixtures) and electrochemical oxidation are also employed in the purification of CNTs [19]. Hammadi et al. [22] reported the purification of CNTs synthesized from liquified petroleum gas by flame fragment deposition using a 2-step process that involved sonicating the produced sample in a hydrogen peroxide solution and then ultrasonication in an acetone bath. Their TEM result indicated that some residual nanocapsules (carbon quantum dots) were unable to be removed using this H₂O/acetone method. Pelech et al. [23] have used two methods in the removal of metals from CNTs. The first step involves the use of acid reflux in nitric acid, and the second method in-

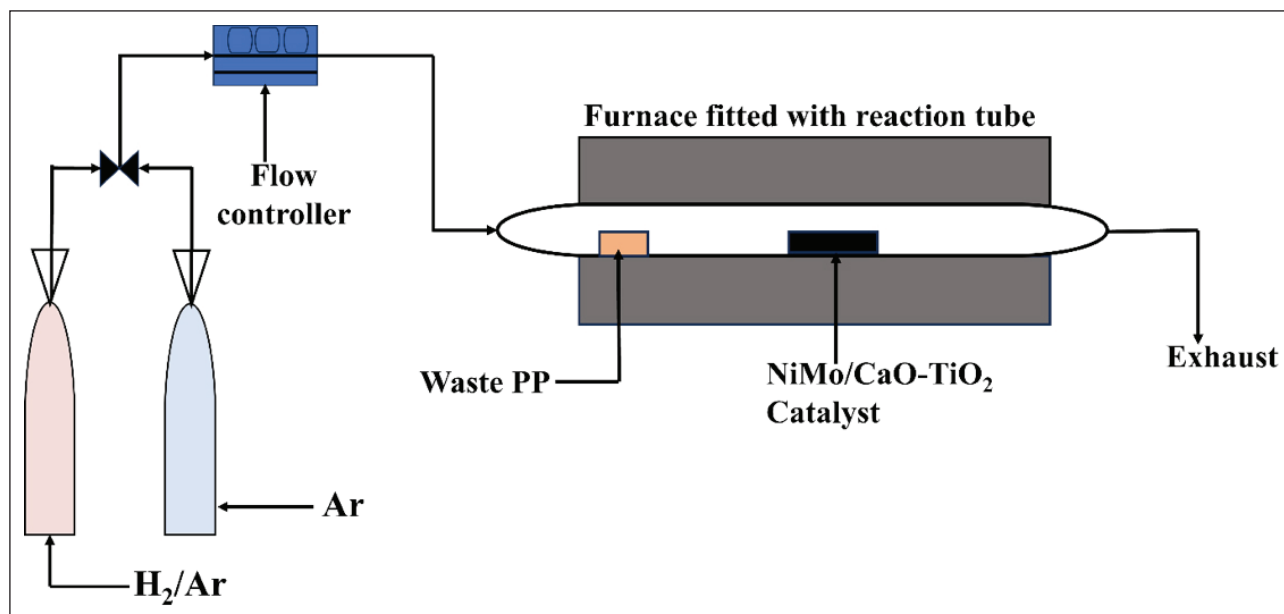


Figure 1. The schematic diagram for the production of CNTs from waste PP using the single-stage CVD technique.

volves microwave-assisted digestion. Their result suggested that microwave heating at elevated pressure improved the purification efficiency, and a similar removal degree was obtained using both acid reflux and microwave-assisted acid digestion techniques.

The physical method is usually used to remove impurities such as nanocapsules and amorphous carbon, or even in the separation of different length and diameter ratios of CNTs. Physical treatment based on ultrasonication, size-exclusion chromatography, filtration, and centrifugation involves the separation of unwanted materials based on variations in gravity, physical sizes, magnetic properties, aspect ratio, and so on [13, 18]. Although some of these physical treatment-based techniques are invariably applied in almost all CNTs' purification studies. A recent study examined the effect of purification on the electrical properties of SWCNTs produced by electric arc discharge using thermal air oxidation and acid oxidation. The reported result showed that purification not only impacted the electrical properties of SWCNTs but also affected the conductivity of SWCNTs, their length, and bundle diameter. Thermal air-oxidized SWCNTs had lower purity but higher conductivity compared to acid-treated SWCNTs [24].

Little or no study in the open literature has essentially evaluated the influence of the various purification protocols on the quality and structure of plastic waste-derived CNTs, despite the growing research interest in the use of plastic wastes as a source of carbon for CNTs synthesis. Plastic waste-derived CNTs have proven to be a sustainable means of eradicating waste and also a viable, cheap, and available hydrocarbon raw material for producing CNTs and other nanomaterials [25]. There is currently no ideal purification method for plastic waste-derived CNTs, as the various purification routes available in the open literature are applied to CNTs produced from different sources. Plastic-derived CNTs have a higher impurity density due to their inherent

complex hydrocarbon nature. Therefore, this study aimed to investigate the effect of three different purification methods on the structural morphology and purity of polypropylene (PP) waste-derived CNTs. This approach is necessary to open up more research efforts towards expanding the possible applications of plastic (wastes)-derived CNTs in other fields of science.

MATERIALS AND METHODS

Materials

Already prepared catalyst: Ni-Mo/CaO-TiO₂ catalyst used in this work was obtained from a previous study [26]. De-ionized water (DI water) and nitric acid (Sigma-Aldrich, South Africa, AR, 65% purity) were utilized in the purification process.

Synthesis of CNTs from PP Waste

The University of Johannesburg, Doornfontein campus's garbage deposit/pick-up point provided the waste PP material used (waste PP consisting of household food packaging was collected at the mentioned garbage point above). The obtained waste materials were then washed, dried, and broken into small bits using a jaw crusher (Retsch SM 200). The experiment's setup is comparable to that which has been previously described elsewhere [27], as shown in Figure 1. The system consists of a quartz tube reactor fitted into a tubular furnace, a gas supply system coupled to a gas flow control meter, and a discharge gas bubbler connected at the reactor end. A boat (quartz) containing 1 g of the already-calcined catalyst sample was placed at the center of the reactor. The catalyst was reduced in situ under a 120 mL/min H_2/Ar gas atmosphere at 700 °C ramped at 20 °C/min for 30 minutes. Once the in-situ reduction was completed, the H_2/Ar gas mixture was disconnected, the gas flow was switched to Ar , and the flow rate was decreased

to 100 mL/min. Then, 2 g of PP waste in a quartz boat was gently introduced into the reactor for deposition and subsequent nanomaterial formation for 30 minutes. The reactor and its components were then left to cool overnight in an environment of Ar. To guarantee that the experiment could be replicated and that the findings were reliable, the experiment was repeated three times, and the average value of the yield was noted. The yield of carbon deposition was calculated based on the mass difference between the fresh and spent catalysts with respect to the mass of waste PP feedstock used, as described by [28]. The experimental setup for the synthesis of CNTs from waste PP feedstock is shown in Figure 1.

The obtained black product was utilized of as-synthesised (pristine) nanomaterial which were individually purified using (1) air oxidation (2) chemical (acid treatment) oxidation, and (3) both chemical & air oxidation techniques, as outlined in the next section.

Purification of CNTs

Synthesized pristine CNTs were firstly pulverized using agate mortar and pestle into powder and were purified using three different purification protocols:

Air oxidation: In this method, 20 mg of the powdery pristine CNTs sample was subjected to thermal oxidation in air from room temperature to 450 °C at a ramp rate of 10 °C / min. and held for 4 hours using a tube furnace. The purified sample is labelled CNT-PA.

Acid oxidation treatment: 20 mg of pristine sample were refluxed in nitric acid for 24 hours at 80 °C and then filtered (over a 0.45 µm membrane). The filtered sample was hydrolyzed by ultrasonication in DI water for 6 hours. Afterward, it was washed several times with DI water until the pH = 7. The sample was then dried at 80 °C in a vacuum oven for 24 hours. The purified sample was labelled CNT-PC.

Multi-step treatment (involving both acid oxidation and air (gas) oxidation: The pristine material was firstly oxidized in air and further treated in acid. About 20 mg of pristine sample was heated in air from room temperature to 450 °C and held for 4 hours. Thereafter, the air-oxidized sample was further refluxed in nitric acid for 24 hours at 80 °C, filtered, hydrolyzed, and ultrasonicated in DI water for 6 hours. The sample was further centrifuged and washed with DI water until the pH was neutral (pH= 7). The purified sample was dried at 80 °C in a vacuum oven for 24 hours and the sample was labelled as CNT-PAC.

The pristine CNTs, that is, the unpurified CNTs sample was labelled as CNT-P0. The pristine sample was hydrolyzed and sonicated in DI water for 6 hours and subsequently dried in a vacuum oven for 24 hours at 80 °C.

Characterization of Purified Nanostructure

The microstructure of purified nanomaterials was determined using a JEM-2100 transmission electron microscope (TEM) instrument (operated at an accelerated voltage of 200 k, with maximum resolution and magnification of 0.23

nm and 1500000x, respectively). A minute amount of the sample was sprinkled in ethanol and sonicated for 7 min; then few droplets of the mixture were carefully distributed onto a copper grid (carbon-coated), dried, and ready for image capture.

The degree of purity and defectiveness of purified and pristine nanomaterials were established using Raman Spectroscopy analysis using WITec focus innovations Raman spectrometer which was excited with the 632 nm laser line in the range of 500 to 3000 cm⁻¹.

The Thermogravimetric analysis (TGA) was conducted to evaluate the purity and the thermal stability of all purified and as-synthesized carbon products using the STA-7200RV HITACHI (Tokyo, Japan) thermal analyzer system from 100 to 900 °C in air.

The functional groups on the side walls and surfaces of purified and pristine nanomaterials were identified by Fourier Transform Infrared (FTIR) analysis using the KBr pellet technique on spectrum 100 FTIR spectrometer (Perkin-Elmer, Waltham, USA) scanned from 1000 to 4000 cm⁻¹.

X-ray diffraction patterns of all purified and as-prepared CNTs were obtained using a Rigaku Ultima 1V X-ray diffractometer (Czech Republic). Samples were X-rayed and recorded in the 2-theta range of 20–80 degrees with Cu Kα radiation, operating at 30 mA and 40 kV. The analysis of the data was carried out using PDXL (2.7.2.0) software.

RESULTS AND DISCUSSION

Effect of Purification Techniques on the Morphology of Plastic-Derived CNTs

Figure 2 depicts the TEM micrographs of pristine CNTs and all purified CNTs using different purification techniques. CNT-P0 consists of amorphous carbon, and residual metal catalysts appearing as black particles inside and outside the walls and on the tips of as-produced CNTs. Also, the presence of other graphitic materials, such as nanofiber, could be observed. Chemical treatment with nitric acid resulted in the rupturing of the wall structure and shortening of the tubes, as shown in Figure 2C, and indicated with arrows at several points in the micrograph. However, it was effective in removing most of the metal nanoparticles. The air oxidation technique was able to remove most of the amorphous carbon impurities and more importantly, this protocol did not create sidewall defects or damage the CNTs' wall as indicated in Figure 2B. However, a large portion of metal nanoparticles were not adequately removed using the air oxidation technique. A similar observation was reported by Clancy et al. [21] during their investigation on air purification of SWCNTs.

Multi-step treatment involving both gas phase oxidation and chemical oxidation treatment, as shown in Figure 2D, also presented some degree of defects on the CNTs wall structure, but a majority of both amorphous carbon and metal nanoparticles were significantly removed using this

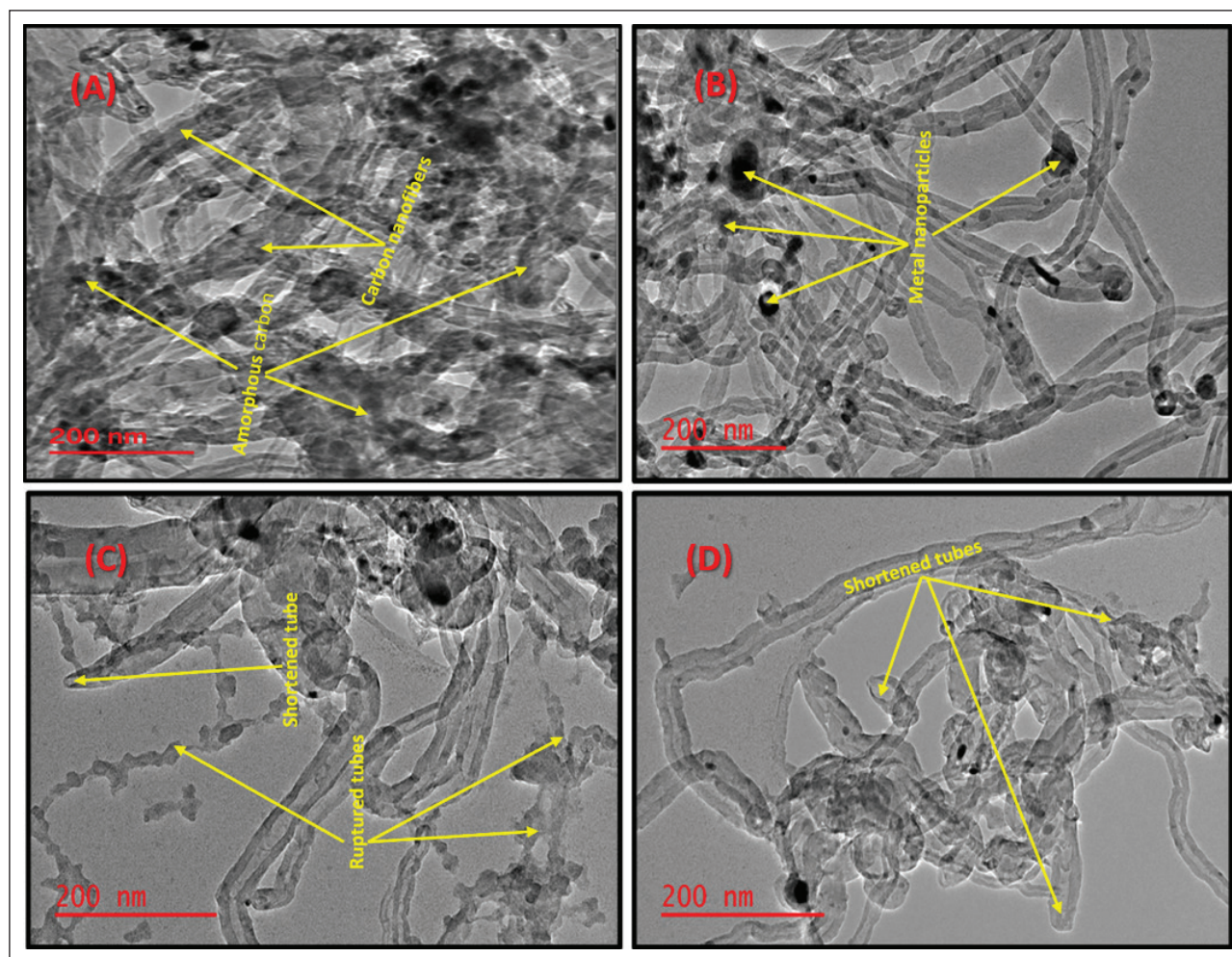


Figure 2. TEM micrographs of all purified and as-synthesized plastic waste-derived CNTs: (A) CNT-P0, (B) CNT-PA, (C) CNT-PC, and (D) CNT-PAC.

technique. Therefore, gas phase oxidation treatment (CNT-PA) resulted in less defective wall structure compared to the other two investigated techniques (both multi-step treatment and chemical oxidation treatment).

Effect of the Various Purification Methods on the Quality of Plastic Waste-Derived CNTs

Figure 3 shows the Raman spectra of all purified and pristine plastic waste-derived CNTs. A Raman spectroscopy study can be used to determine the crystallinity and degree of graphitization of CNTs [29, 30]. Therefore, the Raman spectra in Figure 3 depict three characteristic bands at 1345 cm^{-1} , 1574 cm^{-1} , and 2677 cm^{-1} identified as D, G, and G' (or 2D) bands, respectively. The D-band defines the disorder and defects in CNTs. The G-band is linked to the primary in-plane vibrations of $2p^2$ carbon atoms in graphene [31], while the G' (or 2D) band is related to the inter-valley two-phonon second-order Raman scattering process [32].

The peak intensity ratio of D to G (I_D/I_G) is considered to be proportional to the extent of disorder (graphitization) and purity of CNTs [33]. Therefore, a high I_D/I_G ratio signifies the presence of defects or disorders in the carbon lattice structure which means reduced crystallinity. The peak intensity

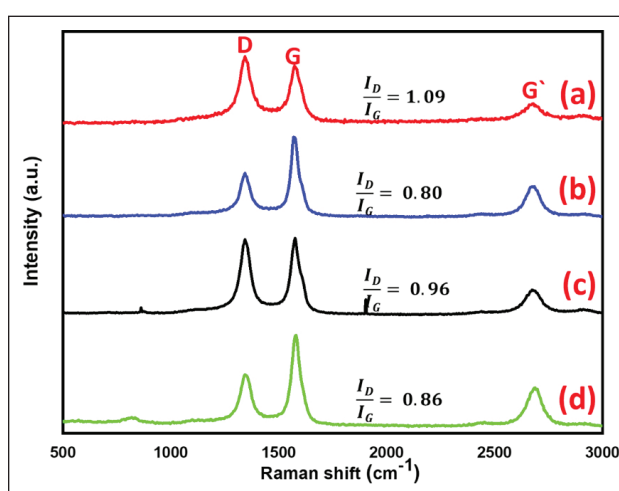


Figure 3. Raman spectra of pristine and all purified plastic waste-derived CNTs: (a) CNT-P0, (b) CNT-PA, (c) CNT-PC, and (d) CNT-PAC.

ratio of G' to G ($I_{G'}/I_G$) is also indicative of the graphene content (graphitization) and stacking of the graphene layer. Amongst the investigated purification methods, CNT-PC showed the highest I_D/I_G ratio of 0.96 followed by CNT-

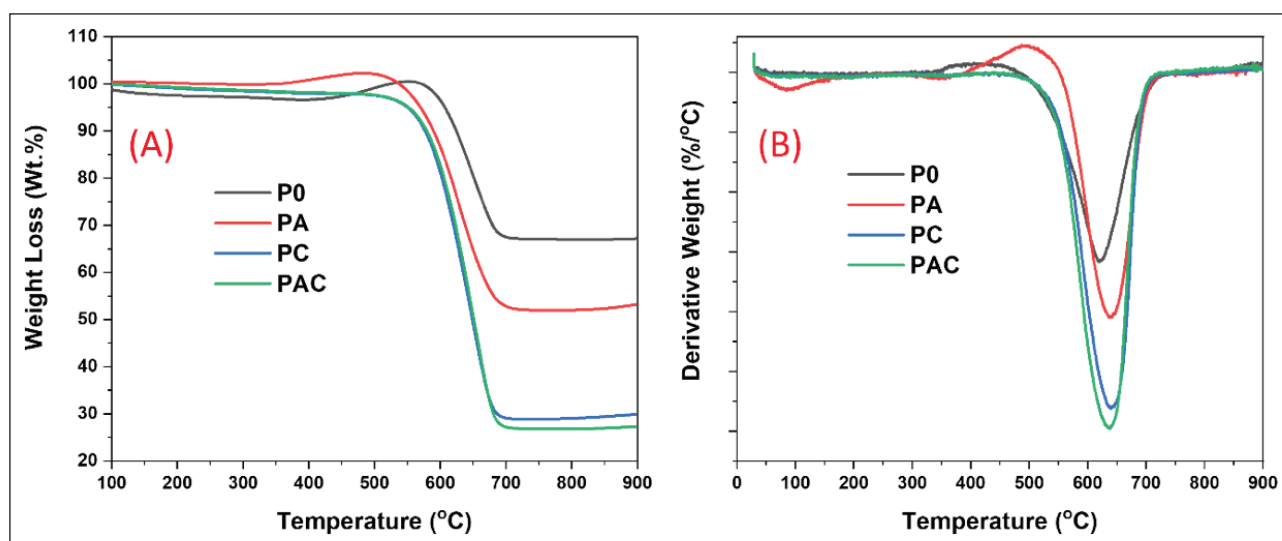


Figure 4. (A) TGA and (B) DTG thermographs of all purified and as-synthesized plastic waste-derived CNTs.

PAC and CNT-PA at 0.86 and 0.80, respectively. As shown in Figure 3, CNT-PA showed the least defect on the CNTs' walls compared to CNT-PC, which had the highest defect density. Therefore, the best quality CNTs were obtained in CNT-PA with the lowest I_D/I_G value. On the other hand, among the investigated purification protocols, the highest I_D/I_G value was obtained in CNT-PC indicating the lowest quality. The I_G/I_G ratio of CNT-PAC was 0.89 indicating the high graphitic structure which means that air and chemical oxidation were able to remove a considerable portion of impurities from the graphene layers. Therefore, CNT-PC presented the highest defective and disordered CNTs compared to the other treatment approaches investigated; this observation is in good agreement with the result obtained from the TEM analysis.

For the non-purified CNTs (CNT-P0), the D- band showed a larger and broader peak. Also, the weak G'-band peak is indicative of the presence of higher irregularities (reduced purity and quality) in the stacking of the graphene layers [34] which may be due to the presence of other impurities such as complex graphitic structures, amorphous carbon, and metal nanoparticles.

Figure 4 depicts the thermogravimetric curves of weight and derivative weight with respect to the oxidation temperature. Temperature-programmed oxidation (TPO) analysis provides salient information about the weight losses and thermal stability of purified and unpurified CNTs. The oxidation of carbon products in air into carbon dioxide results in the weight loss and is suggestive of the type and amount of carbon product present [35]. The catalyst mass losses were 70.1, 30.8, 48.2, and 72.3% for CNT-PC, CNT-P0, CNT-PA and CNT-PAC, respectively. The highest weight loss is associated with the highest carbon deposits [28]. Therefore, for all the purification protocols employed, CNT-PAC with the highest catalyst mass loss showed that almost all the catalyst nanoparticles were oxidized, indicating the highest quality. This finding is consistent with the Raman analysis result.

A higher oxidation temperature is linked to the higher graphitization degree of carbon products [36]. The oxidation peak of non-crystalline carbon, such as amorphous carbon, is reported to be at a lower temperature, usually between 350 and 400 °C, while crystalline filamentous carbon materials show a high-temperature peak above 500 °C [37]. For all purified nanomaterials, the oxidation peak was at 640 °C compared to the as-produced nanomaterial, which had an oxidation peak at 622 °C. Hence, all purified nanomaterials were more thermally stable than as-synthesized nanomaterials, suggesting a higher content of filamentous carbon.

The IR analysis is used to investigate the occurrence of functional groups (-OH, -C=O, -COOH, etc.) on the surfaces and sidewalls of the nanomaterials. The purification process usually results in the opening of end caps and cutting of nanotubes, with the corresponding attachment of functional groups [38, 39].

Figure 5 depicts the FTIR spectra showing the various surface functional groups present in all purified and as-synthesized plastic waste-derived CNTs. The peaks at 3707, 3742, 3779, and 3836 cm^{-1} are assigned to the stretching vibrations of the hydroxyl (-OH) group. Similarly, the well-defined peaks at 3450 cm^{-1} in Figure 5b and c are apportioned to the O-H band in C-OH [40] indicative of the stretching vibrations of hydroxyl (-OH) group arising from the oxidation on the sidewalls of CNTs. The bands at 2917 and 2920 cm^{-1} in Figure 5a and d are assigned to asymmetric stretching of C-H and C-O stretching vibrations, respectively. The peaks at 1580, 1590, 1634, and 1638 cm^{-1} are ascribed to the C=C stretching vibration which is indicative of the skeletal graphite structure of CNTs. Also, the peaks at 1383, 1387, 1389, and 1392 cm^{-1} are distinctive of the asymmetric/symmetric methyl stretching bands due to the deformation vibration of the C-H bond [41]. The peaks at 1210 and 1124 cm^{-1} in Figure 5c and d can be attributed to the C-H and C-O stretching mode which is associated with ether and epoxy groups arising from the oxidation of the nanotubes, which resulted in defective sidewalls, and band

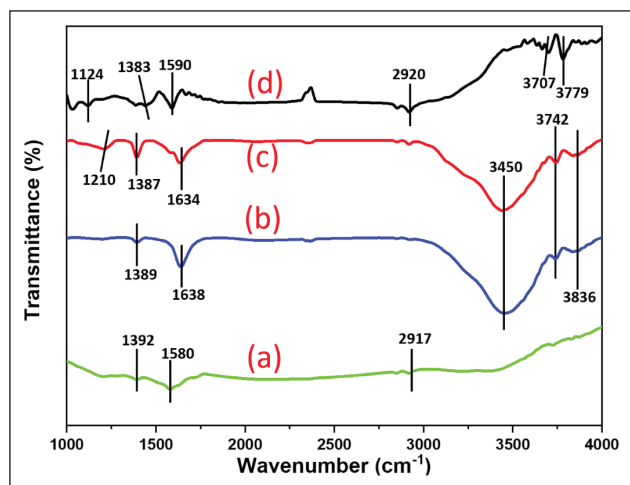


Figure 5. FTIR spectra of purified and pristine plastic waste-derived CNTs: (a) CNT-P0, (b) CNT-PA, (c) CNT-PC, and (d) CNT-PAC.

overlapping, showing the extent of attack on the hexagonal carbon or the carbon-double bond at the sidewalls [42, 43]. This showed that hydroxyl (-OH) and carbonyl (-C=O) groups are introduced on the nanotube sidewall surfaces; a similar observation was reported by [40]. Therefore, both CNT-PAC and CNT-PC showed the attachment of more functional groups on the defective ends of the nanotubes. The purification protocol by acid oxidation and multi-step treatment resulted in nanotube functionalization.

The XRD patterns of pristine and all purified nanomaterials are shown in Figure 6. Diffraction peaks relating to graphite and residual metal catalysts were all labeled as shown. Characteristic graphite (CNTs) diffraction peaks related to (002), (004), and (110) planes which are linked to the atomic pair distribution function PDF 00-058-1638, were identified for all investigated purified and pristine nanomaterials.

The (002) diffraction plane also called Bragg peaks, is primarily used to describe the degree of alignment and distance between two graphene layers in the lattice [44, 45], and this diffraction peak appeared at 26.2° on the two-theta scale. For all purified CNTs, a d-spacing of 0.342 nm was obtained. The d-spacing of the crystalline carbon is evaluated using Bragg's equation $d = \lambda / 2\sin\theta$ [46].

It could be observed that the (002) peak for CNT-P0 showed a slight broadening as compared to all purified CNTs, while the purification treatment under both thermal (air) and/or chemical oxidation techniques causes a reduction in the (002) peak intensity and interlayer spacing between the graphene sheets, confirming the removal of impurities since a decrease in the intensity of this peak depicts higher nanotube alignment [10]. This observation is similar to the result reported by Abdulrazzak and co-workers [47], where the presence of amorphous form of carbon resulted in an increased intensity and width of the (002) peak.

(002) and (004) peaks are employed to relate the interlayer distance within the graphene layers in the nanotube [47]. Another characteristic diffraction peak related to graphite

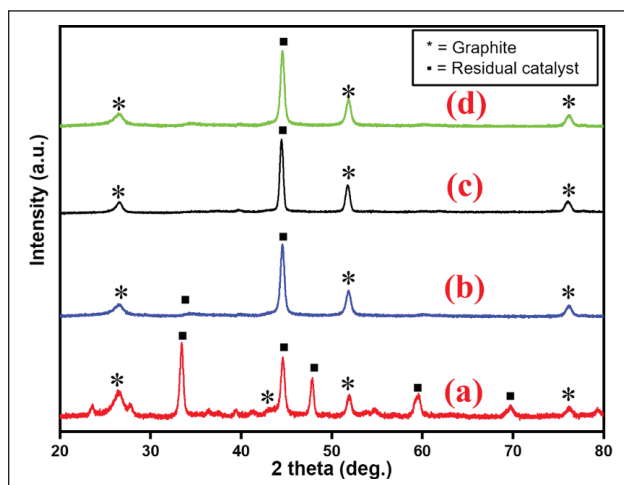


Figure 6. XRD patterns of as-synthesized and all purified plastic waste-derived CNTs: (a) CNT-P0, (b) CNT-PA, (c) CNT-PC, and (d) CNT-PAC.

(CNTs), which corresponds to the (100) plane, was detected in CNT-P0 at the two-theta position of 43.7°. This plane (100) describes the in-plane irregularity; according to Das et al. [48], the intensity of the (100) peak systematically decreases or disappears when all planes of the graphene sheets in the nanotubes are parallel to the (002) diffraction plane. Hence, it could be observed that the intensity of the (100) peak disappeared in all purified samples, suggesting that the intensity of this peak is sensitive to all the purification treatments and that all the planes in the purified CNTs are parallel to the Bragg peak. This elucidates that the treatment procedures undertaken treatment procedures impacted the nanotube's structures and graphitization. This observation correlates with the results obtained in TEM and Raman spectroscopy analyses.

The presence of other graphite (PDF 00-041-1487) and (PDF 00-056-0159) diffraction peaks were also detected in the XRD pattern of CNT-P0. The presence of arrays of diffraction peaks emanating chiefly from Ni metal catalyst impurities (PDF 00-004-0850) was identified in abundance in CNT-P0, followed by CNT-PA compared to other purified samples, this observation is in good agreement with the results obtained in the TEM, Raman, and TG analyses. Suggesting that acid oxidation and multi-step treatment approaches significantly removed practically all metal catalyst impurities from the synthesized samples.

CONCLUSION

The purification of plastic waste-derived CNTs was successfully carried out using three approaches: air-phase (gas) oxidation, liquid-phase (acid) oxidation, and multi-step oxidation. High-quality and pure CNTs can be obtained using the multi-step treatment method while taking advantage of combining the two protocols (both air and acid oxidation) which is also dependent on the intended application. From the results obtained from the XRD, Raman spectroscopy, and TEM analysis, it is shown that CNT-PC (acid/chemical treatment

with nitric acid) presented the highest defects with significant structural and wall transformations, which may be due to the longer refluxing time. CNT-PAC presented the best graphitic structure and fewer defective CNTs compared to others, with an I_G/I_G value of 0.89 and ID/IG value of 0.86, while CNT-PA offered better structural and morphological CNTs and resulted in no loss in CNTs. Again, the chemically treated CNTs (CNT-PC) presented more structurally defective CNTs and shortened nanotubes with an ID/IG value of 0.96. CNT-PAC showed the highest weight loss of 72.3% indicating the highest quality and quantity of filamentous carbon present. Therefore, the structure and morphology of CNTs produced from plastic waste could be controlled by selecting suitable treatment conditions. However, it is recommended that shorter reflux time should be undertaken to minimize and control the possible damage to the CNTs wall structure when using the liquid-phase (acid treatment) approach.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the support received from the University of Johannesburg (UJ), South Africa, under the Global Excellence Stature (GES) fellowship 4.0.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

REFERENCES

- [1] L. Yaqoob, T. Noor, and N. Iqbal, "Conversion of plastic waste to carbon-based compounds and application in energy storage devices," *ACS Omega*, Vol. 7, pp. 13403–13435, 2022. [\[CrossRef\]](#)
- [2] R. Rao, C.L. Pint, A.E. Islam, R.S. Weatherup, S. Hofmann, E.R. Meshot, F. Wu, C. Zhou, N. Dee, P.B. Amama, J. Carpena-Nuñez, W. Shi, D.L. Plata, E.S. Penev, B.I. Yakobson, P.B. Balbuena, C. Bichara, D.N. Futaba, S. Noda, H. Shin, K.S. Kim, B. Simard, F. Mirri, M. Pasquali, F. Fornasiero, E.I. Kauppinen, M. Arnold, B.A. Cola, P. Nikolaev, S. Arepalli, H. M. Cheng, D. N. Zakharov, E.A. Stach, J. Zhang, F. Wei, M. Terrones, D.B. Geohegan, B. Maruyama, S. Maruyama, Y. Li, W. W. Adams, and A. J. Hart, "Carbon nanotubes and related nanomaterials: Critical advances and challenges for synthesis toward mainstream commercial applications," *ACS Nano*, Vol. 12, pp. 11756–11784, 2018. [\[CrossRef\]](#)
- [3] A. Eatemadi, H. Daraee, H. Karimkhanloo, M. Kouhi, N. Zarghami, A. Akbarzadeh, M. Abasi, Y. Hanifehpour, and S. W. Joo, "Carbon nanotubes: properties, synthesis, purification, and medical applications," *Nanoscale Research Letters*, Vol. 9, Article 393, 2014. [\[CrossRef\]](#)
- [4] C.E.M. Oliveira, E.E. da Silva, E.A. de Moraes, V. Geraldo, "Carbon nanotubes research developments: Published scientific documents and patents, synthesis, and production," in: J. Abraham, S. Thomas, N. Kalarikkal (Eds.), *Handb. Carbon Nanotub.*, Springer Nature Switzerland AG, Cham, Switzerland, pp. 1937–1974, 2022. [\[CrossRef\]](#)
- [5] S. Temizel-Sekeryan, F. Wu, and A. L. Hicks, "Global scale life cycle environmental impacts of single- and multi-walled carbon nanotube synthesis processes," *International Journal of Life Cycle Assessment*, Vol. 26, pp. 656–672, 2021. [\[CrossRef\]](#)
- [6] B.O. Murjani, P. S. Kadu, M. Bansod, S. S. Vaidya, and M. D. Yadav, "Carbon nanotubes in biomedical applications: current status, promises, and challenges," *Carbon Letters*, Vol. 32, pp. 1207–1226, 2022. [\[CrossRef\]](#)
- [7] H. U. Modekwe, O. O. Ayeleru, M. A. Onu, T. T. Nyam, M. A. Mamo, K. Moothi, M. O. Daramola, and P. A. Olubambi, "The current market for carbon nanotube materials and products," in: J. Abraham, S. Thomas, N. Kalarikkal (Eds.), *Handb. Carbon Nanotub.*, Springer Nature Switzerland AG, Cham, Switzerland, pp. 619–633, 2022. [\[CrossRef\]](#)
- [8] E. Inshakova, A. Inshakova, and A. Goncharov, "Engineered nanomaterials for energy sector: Market trends, modern applications and future prospects," *IOP Conference Series: Materials Science and Engineering*, Vol. 971, Article 032031, 2021. [\[CrossRef\]](#)
- [9] U.P.M. Ashik, W.M.A.W. Daud, and J. Hayashi, "A review on methane transformation to hydrogen and nanocarbon: Relevance of catalyst characteristics and experimental parameters on yield," *Renew. Sustain. Energy Review*, Vol. 76, pp. 743–767, 2017. [\[CrossRef\]](#)
- [10] R. Das, M. E. Ali, S.B. Abd Hamid, M.S.M. Annur, and S. Ramakrishna, "Common wet chemical agents for purifying multiwalled carbon nanotubes," *Journal of Nanomaterials*, Vol. 2014, pp. 237, 2015. [\[CrossRef\]](#)
- [11] X. Jia, and F. Wei, "Advances in production and applications of carbon nanotubes," *Topics in Current Chemistry*, Vol. 375, Article 18, 2017. [\[CrossRef\]](#)
- [12] H. U. Modekwe, M. A. Mamo, K. Moothi, and M. O. Daramola, "Effect of different catalyst supports on the quality, yield and morphology of carbon nanotubes produced from waste polypropylene plastics," *Catalysts*, Vol. 11, Article 692, 2021. [\[CrossRef\]](#)
- [13] A. F. Ismail, P. S. Goh, J. C. Tee, S. M. Sanip, and M. Aziz, "A review of purification techniques for carbon nanotubes," *Nano Reports Reviews*, Vol. 3, pp. 127–143, 2008. [\[CrossRef\]](#)

- [14] P. Pandey, M. Dhiman, A. Kansal, and S. P. Subudhi, "Plastic waste management for sustainable environment: techniques and approaches," *aste Disposal & Sustainable Energy*, Vol. 5, pp. 205–222, 2023. [\[CrossRef\]](#)
- [15] PlasticsEurope, "Plastics-the Facts 2019. An analysis of European plastics production, demand and waste data," Belgium, 2019.
- [16] R. Geyer, J. R. Jambeck, and K. L. Law, "Production, use, and fate of all plastics ever made," *Science Advances*, Vol. 3, pp. 25–29, 2017. [\[CrossRef\]](#)
- [17] K.L. Law, "Plastics in the marine environment," *Annual Review of Marine Science*, Vol. 9, pp. 205–229, 2017. [\[CrossRef\]](#)
- [18] P.-X. Hou, C. Liu, and H.-M. Cheng, "Purification of carbon nanotubes," *Carbon*, Col. 46, pp. 2003–2025, 2008. [\[CrossRef\]](#)
- [19] P. Mahalingam, B. Parasuram, T. Maiyalagan, and S. Sundaram, "Chemical methods for purification of carbon nanotubes- A Review," *Journal of Environmental Nanotechnology*, Vol. 1, pp. 53–61, 2012.
- [20] S. Boncel, and K. K. K. Koziol, "Enhanced graphitization of c-CVD grown multi-wall carbon nanotube arrays assisted by removal of encapsulated iron-based phases under thermal treatment in argon," *Applied Surface Science*, Vol. 301, pp. 488–491, 2014. [\[CrossRef\]](#)
- [21] A. J. Clancy, E. R. White, H. H. Tay, H. C. Yau, and M. S. P. Shaffer, "Systematic comparison of conventional and reductive single-walled carbon nanotube purifications," *Carbon*, Vol. 108, pp. 423–432, 2016. [\[CrossRef\]](#)
- [22] A. H. Hammadi, A. M. Jasim, F. H. Abdulrazzak, A. M. A. Al-Sammarraie, Y. Cherifi, R. Boukherroub, F. H. Hussein, "Purification for carbon nanotubes synthesized by flame fragments deposition via hydrogen peroxide and acetone," *Materials (Basel)*, Vol. 13, Article 2342, 2020. [\[CrossRef\]](#)
- [23] I. Pelech, U. Narkiewicz, A. Kaczmarek, A. Jedrzejewska, "Preparation and characterization of multi-walled carbon nanotubes grown on transition metal catalysts," *Polish Journal of Chemical Technology*, Vol. 16, pp. 117–122, 2014. [\[CrossRef\]](#)
- [24] J. C. Goak, S. H. Lee, and N. Lee, "Effect of purification on the electrical properties of transparent conductive films fabricated from single-walled carbon nanotubes," *Diamond and Related Materials*, Vol. 106, Article 107815, 2020. [\[CrossRef\]](#)
- [25] A. Ahamed, A. Veksha, K. Yin, P. Weerachanchai, A. Giannis, and G. Lisak, "Environmental impact assessment of converting flexible packaging plastic waste to pyrolysis oil and multi-walled carbon nanotubes," *Journal of Hazardous Materials*, Vol. 390, Article 121449, 2020. [\[CrossRef\]](#)
- [26] H. U. Modekwe, M. A. Mamo, M. O. Daramola, and K. Moothi, "Catalytic performance of calcium titanate for catalytic decomposition of waste polypropylene to carbon nanotubes in a single-stage CVD reactor," *Catalysts*, Vol. 10, Article 1030, 2020. [\[CrossRef\]](#)
- [27] H. U. Modekwe, M. Mamo, K. Moothi, and M. O. Daramola, "Synthesis of bimetallic NiMo/MgO catalyst for catalytic conversion of waste plastics (polypropylene) to carbon nanotubes (CNTs) via chemical vapour deposition method," *Materials Today: Proceedings*, Vol. 38, pp. 549–552, 2021. [\[CrossRef\]](#)
- [28] D. Yao, and C. H. Wang, "Pyrolysis and in-line catalytic decomposition of polypropylene to carbon nanomaterials and hydrogen over Fe- and Ni-based catalysts," *Applied Energy*, Vol. 265, Article 114819, 2020. [\[CrossRef\]](#)
- [29] M. Flygare, and K. Svensson, "Quantifying crystallinity in carbon nanotubes and its influence on mechanical behaviour," *Materials Today Communications*, Vol. 18, pp. 39–45, 2019.
- [30] A. Jorio, and R. Saito, "Raman spectroscopy for carbon nanotube applications," *Journal of Applied Physics*, Vol. 129, Article 021102, 2021. [\[CrossRef\]](#)
- [31] D. Yao, H. Yang, H. Chen, and P. T. Williams, "Co-precipitation, impregnation and so-gel preparation of Ni catalysts for pyrolysis-catalytic steam reforming of waste plastics," *Applied Catalysis B: Environmental*, Vol. 239, pp. 565–577, 2018. [\[CrossRef\]](#)
- [32] M. S. Dresselhaus, G. Dresselhaus, R. Saito, and A. Jorio, "Raman spectroscopy of carbon nanotubes," *Physics Reports*, Vol. 409, pp. 47–99, 2005. [\[CrossRef\]](#)
- [33] A. A. Aboul-Enein, and A. E. Awadallah, "Impact of Co/Mo ratio on the activity of CoMo/MgO catalyst for production of high-quality multi-walled carbon nanotubes from polyethylene waste," *Materials Chemistry and Physics*, Vol. 238, Article 121879, 2019. [\[CrossRef\]](#)
- [34] E. C. Igbokwe, M. O. Daramola, and S. E. Iyuke, "Production of carbon nanotube yarns via floating catalyst chemical vapor deposition: Effect of synthesis temperature on electrical conductivity," *Results in Physics*, Vol. 15, Article 102705, 2019. [\[CrossRef\]](#)
- [35] J. Jia, A. Veksha, T. Lim, and G. Lisak, "In situ grown metallic nickel from X-Ni (X= La , Mg , Sr) oxides for converting plastics into carbon nanotubes: Influence of metal support interaction," *Journal of Cleaner Production*, Vol. 258, pp. 1–11, 2020. [\[CrossRef\]](#)
- [36] J. C. Acomb, C. Wu, and P. T. Williams, "The use of different metal catalysts for the simultaneous production of carbon nanotubes and hydrogen from pyrolysis of plastic feedstocks," *Applied Catalysis B: Environmental*, Vol. 180, pp. 497–510, 2016. [\[CrossRef\]](#)
- [37] A. A. Aboul-Enein, and A. E. Awadallah, "Production of nanostructure carbon materials via non-oxidative thermal degradation of real polypropylene waste plastic using La₂O₃ supported Ni and Ni–Cu catalysts," *Polymer Degradation and Stability*, Vol. 167, pp. 157–169, 2019. [\[CrossRef\]](#)
- [38] A. B. Makama, A. Salmiaton, N. Abdullah, T. S. Y. Choong, and E. B. Saion, "Recent developments in purification of single wall carbon nanotubes," *Separation Science and Technology*, Vol. 49, pp. 2797–2812, 2014. [\[CrossRef\]](#)

- [39] P. De Luca, C. Siciliano, A. Macario, and J. B. Nagy, "The role of carbon nanotube pretreatments in the adsorption of benzoic acid," *Materials (Basel)*, Vol. 14, Article 2118, 2021. [\[CrossRef\]](#)
- [40] E. M. Elsehly, N. G. Chechenin, A. V. Makunin, H. A. Motaweh, E. A. Vorobyeva, K. A. Bukunov, E. G. Leksina, and A. B. Priselkova, "Characterization of functionalized multiwalled carbon nanotubes and application as an effective filter for heavy metal removal from aqueous solutions," *The Chinese Journal of Chemical Engineering*, Vol. 24, pp. 1695–1702, 2016. [\[CrossRef\]](#)
- [41] H. Hu, T. Zhang, S. Yuan, and S. Tang, "Functionalization of multi-walled carbon nanotubes with phenylenediamine for enhanced CO₂ adsorption," *Adsorption*, Vol. 23, pp. 73–85, 2017. [\[CrossRef\]](#)
- [42] H. U. Modekwe, M. Mamo, K. Moothi, and M. O. Daramola, "Polypropylene waste-derived carbon nanotubes (CNTs) via single-stage CVD technique: Determination of crystallinity," *IOP Conference Series: Materials Science and Engineering*, Vol. 1107, Article 012067, 2021. [\[CrossRef\]](#)
- [43] R. Yudianti, H. Onggo, Sudirman, Y. Saito, T. Iwata, and J. Azuma, "Analysis of functional group sited on multi-wall carbon nanotube surface," *The Open Materials Science Journal*, Vol. 5, pp. 242–247, 2011. [\[CrossRef\]](#)
- [44] A. Cao, C. Xu, J. Liang, D. Wu, and B. Wei, "X-ray diffraction characterization on the alignment degree of carbon nanotubes," *Chemical Physics Letters*, Vol. 344, pp. 13–17, 2001. [\[CrossRef\]](#)
- [45] D. K. Singh, P. K. Iyer, and P. K. Giri, "Diameter dependence of interwall separation and strain in multiwalled carbon nanotubes probed by X-ray diffraction and Raman scattering studies," *Diamond and Related Materials*, Vol. 19, pp. 1281–1288, 2010. [\[CrossRef\]](#)
- [46] D. Yao, H. Yang, Q. Hu, Y. Chen, H. Chen, and P. T. Williams, "Carbon nanotubes from post-consumer waste plastics: Investigations into catalyst metal and support material characteristics," *Applied Catalysis B: Environmental*, Vol. 280, Article 119413, 2021. [\[CrossRef\]](#)
- [47] F. H. Abdulrazzak, A. F. Alkaim, F. H. Hussein, "Behavior of X-Ray analysis of carbon nanotubes," in *Perspect. Carbon Nanotub.*, IntechOpen, London, United Kingdom, 2019. [\[CrossRef\]](#)
- [48] R. Das, S. B. A. Hamid, M. E. Ali, S. Ramakrishna, and W. Yongzhi, "Carbon nanotubes characterization by X-ray powder diffraction – A Review," *Current Nanoscience*, Vol. 11, pp. 1–13, 2015. [\[CrossRef\]](#)



Review Article

Towards net zero energy buildings: A review of barriers and facilitators to the adoption of building energy efficiency practices

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ARTICLE INFO

Article history

Received: 27 June 2023

Revised: 16 September 2023

Accepted: 10 October 2023

Key words:

Building; Carbon emission;
Energy efficiency; Renewable
energy; Sustainable construction

ABSTRACT

With recent and unprecedented attention toward the implementation of Energy efficient building which aids in advocating sustainable construction, numerous attempts have made in establishing flexible approaches to which these practices will assist in savings cost of construction, improve the quality of indoor air as well as lowering the GHG emissions. However, the system is lacking proper and standardized methodology of implementations. Therefore, this study dwelt in examining several factors capable of influencing the application of energy conservation practices in buildings, along with the advantages and barriers for implementation based on existing literatures, which focuses on raising awareness, providing information, implementing proper policies, and creating incentives to provide alternative solutions for building owners. As presented, study's outcomes offer a blueprint for comprehending the nuanced dynamics of building energy efficiency and lay out a clear course for further investigation. The study also, identifies significant factors which majorly influences building energy efficiency which include government supervision, design standards, construction quality, and energy-efficient materials. The study recommends utilizing cutting-edge innovations, building automation systems, and IoT devices to improve energy monitoring and conservation.

Cite this article as: Labaran YH, Mato H, Saini G, Musa AA. Towards net zero energy buildings: A review of barriers and facilitators to the adoption of building energy efficiency practices. Environ Res Tec 2024;7(1)118–130.

INTRODUCTION

As cities grow and populations rise, the need for energy increases at an alarming rate [1, 2]. According to studies, the construction and building industry alone accounts for over 30 percent of all primary energy consumption and contributes significantly to greenhouse gas emissions [3, 4]. However, by improving energy efficiency in buildings, this amount of energy will be decrease and help in sav-

ing resources and lessen the impact to the environmental [5, 6]. Hence, it is crucial for facility managers, building owners, and utility companies to understand energy consumption patterns and make informed judgements on energy-saving measures [7, 8]. Researchers have been fascinated by building energy efficiency for years and have focused mostly on identifying factors that contributes in building energy consumption [9, 10]. In addition to that, numerous experts have related the energy efficiency of

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various buildings to their age, which is particularly an interesting aspect, as older buildings may require more extensive renovations to improve their efficiency [11, 12]. However, it is pertinent to note that even older buildings and structures can be retrofitted to meet energy-efficient standards [13, 14].

Energy efficiency is a crucial aspect of achieving a sustainable future [15]. It involves reducing energy use to the lowest possible level without compromising on living standards, production quality, or profitability [16]. That is to say, instead of abstaining from using energy altogether, energy efficiency focuses on using it in a manner that reduces the amount necessary to operate equipment and services [5, 17]. As such, improving energy efficiency in domestic and industrial buildings is essential in decreasing demand on the main supply plants while maintaining the quality of energy services [18]. This can be accomplished by implementing a well-planned strategy and involving various stakeholders, such as the government and building owners, in the process [19]. In addition, energy efficiency policies are not only beneficial to the environment but also to the economy [2]. Those policies can help market forces and enhance household efficiency, the transportation system, offices, and factories [20]. Also, by consuming energy more efficiently, more resources can be freed up on economic sector and more energy will be available in other sectors [21]. This can help in reducing the need for energy exchange and changes in the electricity supply [22].

The need for building energy efficiency design standards across different climatic zones is crucial to reducing energy consumption [23, 24]. However, achieving these standards can be challenging, this is because they are influenced by several factors, such as occupants' behavior, government oversight, the usage of energy-saving materials, design quality, etc., [13, 23]. Hence, the adoption of energy efficiency practices by owners/occupants can greatly impact the energy demand of an area [25], leading to several benefits including job creation, cost savings, energy security, diverse business opportunities, improved health conditions etc., [5, 26]. Furthermore, energy-efficient buildings do not only improve the use of energy but, also enhance the overall life cycle phases of the buildings [10]. Hence, it's vital for property owners, building occupants, facility managers, and utility providers to comprehend how energy usage in buildings tends to behave and take proactive measures toward enhancing its efficiency [27]. Therefore, by understanding the barriers and implementing effective energy management strategies at the public, private, and residential levels, a realistic significance can be noticed in reducing energy consumption, while promoting sustainability [13].

The main trends in influencing factors for energy-efficient buildings have drastically improved in recent times. Factors that were previously evaluated among those that impact building energy efficiency and those that affect energy efficiency investment in existing residential houses have now been merged with occupant behaviour in building man-

agement [6]. Hence, it is critical to investigate the factors influencing building energy efficiency uptake behaviour in order to identify the energy conservation difficulties in residential dwellings. This justifies the aim of this study at reviewing various contributions by the previous researchers to identify the primary impediments to implementing energy efficiency practices in our buildings.

IMPORTANT PHRASES

Energy Efficiency

As scoped to the buildings, Mitsushima et, al., [28] defined energy efficiency as the capability to generate a substantial output with minimal energy input, usually expressed as a percentage [28]. According to Demirel and Ibrahim [29] efficiency of electric motors can be described as the amount of mechanical energy produced by an electric motor for a given quantity of electrical energy input [29]. The EU Energy Efficiency Directive defines energy efficiency as the ratio of output, such as goods, performance, services, to energy input.

Building Energy Efficiency

This is described as a designing and construction of a buildings in such a manner that the energy required for conditioning, heating and lighting is considerably reduced, independent of the equipment utilised or the energy source used [30, 31].

Household

This refers to one or more people who live together and share meals. This may be a single-family home or any other group of people living together [32]. In many social, microeconomic, and governmental models, the home is regarded as the fundamental unit of study and is crucial to both economics and demography. If living quarters or meals are not shared, a house is thought to contain more than one household.

Net Zero Energy Building (NZEB)

These are structures that yearly produces as much energy as it uses [24]. This is accomplished by employing renewable energy sources, such as wind or solar energy, and by applying energy-efficient design and technologies to decrease energy usage [33]. These buildings are meant to be self-sufficient and eventually consume no energy. Also, the energy consumption of zero energy building should be reduced accordingly to meet the passive house standards.

Renewable Energy

This is often known as clean energy or non-conventional energy, derived from renewable natural resources or production techniques [34]. Although using the power of nature has long been utilised for transportation, lighting, heating, and other purposes, renewable energy is frequently thought of as a relatively recent technology [31]. Wind, sun, biomass, hydropower, and geothermal are all examples of renewable energy sources.

Non-Renewable Energy

This is also referred to conventional energy, which usually generated from resources that cannot be replenished in a short period of time [34]. Fossil fuels including coal, oil, natural gas, and nuclear energy are examples of non-renewable forms of energy. The buried remnants of plants and animals that lived hundreds of millions of years ago are thought to have served as the source of fossil fuels [33].

ENERGY EFFICIENCY: DEFINITIONS AND APPLICATIONS IN BUILDING COMPONENTS

Energy efficiency is an important concept that refers to the equivalent work being completed with less energy. It's a way to reduce energy consumption, lower costs, and minimize the environmental impact of energy use [35, 36]. There are several approaches to achieving energy efficiency, from simple changes in behavior to more complex technological solutions [18]. Among the easiest methods to improve energy savings is by using energy-efficient devices and appliances. Utilizing a compact fluorescent light bulb (CFL) instead of an incandescent bulb, for instance, might save energy as CFLs use less power to produce the same amount of light [37, 38]. This is just one example of how using energy-efficient technology can make a big difference in reducing energy consumption. Another important aspect of energy efficiency is the system and building design itself. Insulating a building can lower the amount of energy required to cool and heat it [39]. Additionally, designing buildings with energy efficiency in mind, might result in lower energy use. This includes using natural lighting, proper ventilation, and making sure that the cooling and heating systems are properly sized for the building [17].

Energy management systems are also key component of energy efficiency. These systems allow users to monitor energy usage and identify areas where energy is being wasted [38]. They can also help in implementing energy-saving strategies and make informed decisions about energy use [22]. In addition to that, energy efficiency can also be achieved through energy conservation, which is the practice of reducing or managing the use of energy. This may be accomplished by taking easy actions like switching off equipment and lights when they're not in use, unplugging chargers and electronics when they are fully charged, and using power strips to reduce standby power usage [18]. Furthermore, energy efficiency can also be achieved through more advanced measures such as implementing building automation systems that can manage HVAC, lighting, and other appliances to minimize energy consumption [16].

Another important aspect is the implementation of energy-efficient practices in industries and businesses. This include upgrading equipment and machinery, implementing energy-efficient processes, and incorporating energy management systems [40]. Not only can this decrease energy consumption, but it can also enhance productivity and competitiveness in the industry [37]. Apart from that, government policies and

Table 1. Guidelines and plans for energy efficiency

Sectors	Guidelines and plans
Appliances efficiency	Technology
Architects	Design
Behavioral	Occupants behavior
Public authority	Compile a comprehensive strategy
Public	Conditional behavior
Private developers	Sustainable housing design and development

incentive programs such as credits for energy-efficient appliances and equipment, financial incentives for making energy-efficient upgrades to existing buildings, and regulations mandating energy-efficient building codes while aide towards promoting the adoption of energy efficiency practices [8, 41]. Overall, energy efficiency is a comprehensive approach that involves a combination of technology, behavior, policies, and regulations to reduce cost and energy usage, while reducing the environmental impact of energy use [42]. It's a vital strategy for addressing climate change, energy security, and economic growth [39]. The Table 1 illustrate some policies to enhance energy efficiency practices [39].

Objectives of Energy Efficiency

Energy efficient buildings provide households with a comfortable and quality indoor environment with low energy consumption. The key to unlocking this sustainable future lies in implementing policies that not only lower energy consumption but also enhance the overall well-being of its inhabitants. To bring this vision to life, a comprehensive energy efficiency policy must be put in place by taking the following three objectives [43].

- i. Provision of livable buildings.
- ii. Provision of resilient buildings.
- iii. Provision of affordable buildings.

3.2. Bioclimatic Architectural Design

Achieving energy efficiency in buildings begins with implementing bioclimatic architectural design [44]. This approach involves designing a building to work in harmony with the local climate, utilizing natural elements such as sunlight, wind etc., to minimize the requirement for artificial cooling and heating [31]. By utilizing bioclimatic design principles, buildings can achieve a comfortable indoor environment while minimizing resources such as energy and water [45]. Not only does this approach led to cost savings, but it also improves the overall well-being of the building's inhabitants [44]. Figure 1 outlines the procedure for incorporating bioclimatic strategies into building design [43].

3.3. Energy efficient Mechanical Systems

In addition to using bioclimatic techniques, active systems such as air conditioning are necessary to ensure the comfort and well-being of building occupants. To be resource-effi-



Figure 1. Bioclimatic design sequence [43].

cient, appliances and energy efficiency measures should be used as needed [44]. That is to say, after successfully reducing heat sources from outside, the next step is to decrease the quantity of heat produced within the building through efficient cooling [31].

3.4. Renewable Energy

Passive design and mechanical systems are game-changers when it comes to reducing energy demand. But incorporating renewable energy sources can take the building's performance to the next level [31, 34]. Additionally, incorporating resilient design elements means will result in having less dependency on energy supply, ultimately providing you with peace of mind [46].

Benefits of Implementing Energy-Efficient Building Practices

The energy-efficient building offers numerous advantages to both the environment and the occupants of the building. Some of the key benefits include improved comfort, cost savings, indoor air quality, and a reduction in fossil fuel usage, greenhouse gas emissions, etc., [31, 36]. However, in this study, a concentration will be on three major benefits; environmental, social, and economical benefits as shown in the Figure 2.

3.5.1. Economic Benefits

- Lower energy bills:** Among the most significant economic advantages of an energy-efficient structure is that it can result in decreased cost of energy bills for the building's occupants [20]. This is achieved by using energy-efficient appliances, lighting, and HVAC systems, in addition to implementing energy-efficient building design features like proper insulation and air sealing [30]. These measures can result in significant cost savings for building owners and renters.
- Increased property value:** Another financial advantage of an energy-efficient building is that it can enhance the value of a property [47]. Energy-efficient buildings are more attractive to potential buyers or renters and may be valued higher than similar, less efficient properties. This is because energy-efficient buildings can provide a more comfortable living environment, lower energy bills, and a smaller environmental footprint [47].
- Job creation:** Building energy efficiency can also lead to job creation in related industries such as construction, manufacturing, and engineering. As demand for energy-efficient buildings increases, so too will the need for professionals who can design, build, and maintain these structures [48].

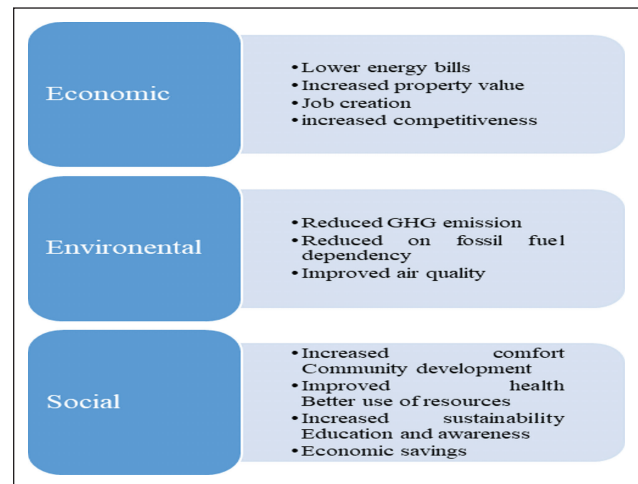


Figure 2. Benefits of building energy efficiency.

- Increased competitiveness:** Building energy efficiency can also help businesses to reduce operating costs and increase their competitiveness in the marketplace. By using less energy, businesses can decrease their energy expenses and pass on savings to their customers [49].

3.5.2. Environment Benefits

- Reduced greenhouse gas (GHG) emissions:** Among the significant environmental benefits of building energy efficiency is that it can lower the amount of GHG emissions linked to electricity generation [38]. As such, by consuming less energy, buildings lessen their carbon footprint and contribute towards combating global warming [33].
- Reduced dependence on fossil fuels:** Building energy efficiency can also decrease reliance on fossil fuels, which are a limited resource as well as a leading cause of global warming [38]. Hence, by using less energy, buildings can lessen reliance on fossil fuels and their environmental consequences [50].
- Improved air quality:** Building energy efficiency can also enhance indoor air quality by minimizing the number of pollutants and moisture that can enter the building [50]. This can be achieved by using high-efficiency air filters, proper ventilation, and controlling indoor humidity levels [30]. Moreover, the health and well-being of the building's occupants may be positively impacted by better indoor air quality, which may also lessen allergy and asthma symptoms [51].

3.5.3. Social Benefits

- Increased comfort:** Building energy efficiency can lead to increased comfort for the people living or working

inside the building. This is achieved by controlling temperature and humidity, improving indoor air quality, and providing natural daylight. Energy-efficient building design and technology can also help to reduce drafts and eliminate hot and cold spots in a building [30].

- b) Improved health: The health and well-being of the building's occupants may be positively impacted by better indoor air quality, which may also lessen allergy and asthma symptoms [51]. This is an important social benefit that can enhance the general quality of life for those residing in or employing the structure [52].
- c) Increased sustainability: Building energy efficiency may assist to foster a more stable environment for the community as well as the planet by reducing energy consumption and dependence on fossil fuels. This can lead to even more responsible resource usage and a more sustainable future for all [53].
- d) Economic savings: Building energy efficiency can lead to economic savings for building owners, renters, and even the local economy. Lower energy bills and increased property value can contribute to the overall financial well-being of the community [47].
- e) Community development: Job creation and increased competitiveness can lead to community development and growth. As energy-efficient building becomes more prevalent, they can create new opportunities for employment and economic growth [48].
- f) Better use of resources: Building energy efficiency can make better use of resources and reduce the strain on the environment which will help toward conserving natural resources and reducing waste [53].
- g) Education and awareness: Energy efficiency can also help to improve public understanding about the necessity of energy efficiency and environmental responsibility. Hence, by showcasing the advantages of energy conservation, building owners and operators can inspire others to adopt more sustainable practices and promote a culture of conservation [49, 54]. In summary, building energy efficiency offers a wide range of benefits that can positively impact on the society, the economy, and environment as a whole. As such, by investing in energy-efficient building design and technology, building owners, developers, and occupants can reduce their environmental footprint, save money on energy costs, and improve the comfort and health of those who live or work inside the building, as well as contribute to community development and the better use of resources [20].

3.6. Building Energy Efficiency Design Tools

When it pertains to constructing and designing energy-efficient buildings, the right tools and software can make all the difference. With so many options available, it can be overwhelming to know where to start [55]. Luckily, many tools have been created across the world to aid with decision-making and guide the design team and building oc-

cupants into the future [38, 56]. One of the most impactful tools in recent years is simulation-based optimization software. This technology has increased flexibility in the design process, reduced the time required to complete the design, and made the software more user-friendly [57]. This means that not only can you achieve energy efficiency more easily, but you can also do it in less time and with less hassle. The future of energy-efficient building control design is also being shaped by new-generation tools [49]. These tools are based on control-focused features that can improve the overall performance of the building. This means that not only can you design an energy-efficient building, but you can also control and monitor its performance in real-time to ensure that it continues to operate at peak efficiency [58].

Currently, the community is already utilizing advanced control and simulation software and devices to construct energy efficiency. Typical software and technologies used for comprehensive design of buildings includes; Athena, Eco-Bat, the IES Virtual Environment, and Green Building Studio [55]. These tools have been widely adopted and tested, and have proven to be effective in designing energy-efficient buildings. For those looking to design energy-efficient buildings, there are a plethora of options available. Passive house planning packages, Energy Plus, eQuest, HOT 2000, DesignBuilder, IDA-ICEA, Revit, Modelica/Dymola, Simulink/Matlab, and ESP-r are just some of the tools and software available [59, 60]. Each of these options has its unique features and capabilities and can be used to design energy-efficient buildings that are sustainable, and comfortable for their occupants [61].

4. BARRIERS TO ENERGY EFFICIENCY PRACTICES

Energy efficiency barriers can include a lack of methods and tools to calculate energy savings, the absence of financial incentives for energy-efficient equipment, high initial costs for such equipment, challenges in obtaining funding, and difficulties in procuring, deploying, running, and maintaining energy efficiency systems and techniques [62]. According to Seddiki et al., (2009) [63], economic and behavioral barriers are more prevalent in the building sector, while the transportation sector faces more institutional and economic obstacles [64]. However, the expense of executing energy-efficient measures is frequently considered as the most significant obstacle to attaining energy efficiency [65]. The high initial investment required for energy-efficient equipment and retrofits can be a significant obstacle for many building owners and operators; hence, the major barrier across all sectors is the financial barrier [42, 66]. The three main types of barriers to adopting energy efficiency in buildings are depicted in Table 2 [67].

4.1. Behavioral Barriers

Behavioral barriers, including a lack of understanding about the concept of energy conservation and the advantages of non-energy alternatives, a low level of trust, a lack of information, or inconsistent behavior, can all impede

Table 2. Major barriers to energy efficiency practices

Description of barrier types	Description
Behavioral	Cultural saving shortage, savings attentiveness, scarcity of skills, social crowd interface, knowledge scarcity, and information trust.
Institutional	Existence of infrastructural limitation, non-combined goals and confliction strategies, Ineffective legislative initiatives and regulations.
Economical	Insufficient financial resources, indecision of savings, higher risk of investment, and encouragement of monetary shortage.

Table 3. Reviewed studies on the barriers to energy efficiency practices

Barriers	Typical barrier	Sources
Behavior (social, culture)	Habits, custom	[38, 67]
	Lack of interest	[67, 74, 82]
	Unawareness of possible savings	[38, 67, 82]
Economic	Insufficient access to financing	[67, 86, 84]
	Inadequate economic institution to funding renewable energy technologies, inadequate instrument	[82, 86]
	Shortage of commercial feasibility	[87]
Environment	Resource competition, pollution and ecological aspects,	[82]
Misconceptions about renewable energy technology	Uncertainty about new technologies and benefits	[82]
Institutional	Complex regulatory procedure	[67]
	inadequate enforcement of pertinent law	[34, 67, 82]
	Insufficient knowledge and information	[34, 82, 85]
	Inadequate infrastructure	[82, 85]
insufficient infrastructure	Issue with infrastructure accessibility	[82]
Technological	Inadequate training facilities	[82, 86]
	Limited ability to implement innovation	[82]
	Operation and management of technological knowledge are insufficient.	[82]
Uncertainty on public authority	Policy uncertainty and under-equipped agencies	[82]

progress in the realm of energy efficiency and building performance [68, 69]. Occupant behavior is critical in influencing energy use and household well-being, but it is frequently not completely understood or incorporated in building energy efficiency due to its interdisciplinary nature, diversity, and complexity [70, 71]. Traditionally, Tenant behavior has been perceived as a passive component, similar to weather, rather than an active participant in building energy consumption [4, 38]. However, recent studies have revealed the significant impact that occupants can have on building energy consumption, leading to a surge of research in this area [72, 73]. Behavioral barriers also impact transportation habits, with individuals often prioritizing convenience over sustainability due to societal attitudes and customs [42, 45].

4.2. Institutional Barriers

Institutional impediments are linked to obstructionist politics, poor strategy management, and opposing perspectives in government decisions [75, 76] The implementation of en-

ergy-saving measures necessitates the cooperation and coordination of various actors within the sector [77]. As such, inadequate or non-existent support from both commercial and governmental sectors, often stemming from a lack of clear and straightforward administration and collaboration can impede the energy efficiency guidelines' implementation [21, 38]. Previous research has emphasized the necessity of providing clear, concise, and practical explanations of energy-saving initiatives [70]. Streamlining administrative process can aid reduce confusion and the burden on government systems [67, 78]. Hence, a strong vision for energy efficiency set at the highest administrative level is critical in lowering institutional impediments such as uneven governance configurations and guidelines, redundant strategies, and an absence of policy coherence [67, 79].

4.3. Economic Barriers

Economic barriers, such as difficulties in accessing adequate credit and unbalanced existing finance, high threats to shareholders, and institutional finance, are considered to

Table 4. Reviewed studies on the factors influencing the implementations of building energy-efficiency practice

Sources	Features	Factors	Methodology	Conclusion
Annunziata et al., 2014 [90]	The four factors that have been highlighted include:	Capacity building, technical and financial support	Questionnaires were employed for the study.	The findings underline the significance of increasing knowledge efficiency, maintaining and assessing consistency, and establishing a development strategy.
	i. The presence of buildings and capabilities f or energy-efficiency ii. Increasing energy-efficiency capacity iii. Financial and technical assistance iv. Adoption of "low-hanging fruit" energy-saving methods has a knock-on effect.			
Cui et al. 2014 [91]	Technology and management guidelines	Management effects happened as a result of a clean technical efficiency change guide, whilst technology is influenced as a result of a technological advancement change index.	Panel regression Mode	According to the research, management and technological guidelines are the most important influencers on energy efficiency.
Chen, et al., (2020) [6]	The building's features or attributes	Building type, wall insulation, location, window-to-wall ratio, window glazing, ideal insulation thickness, and insulation materials are some of the factors that can be considered when evaluating a building's energy efficiency.	Article review	To assist occupants in making informed decisions, technological innovations, building services, and tenant behavior management must be prioritized.
	Equipment and technologies	Thermal storage, Variable air volume, heat recovery, improved control, and evaporative cooling.		
	Residents' behavior	Smart grid, access to control, smart meter, and plug load.		
Nair et al, 2010 [66]	Contextual factors	Location, perceived energy cost, thermal comfort, building age, and past investment.	Questionnaires were employed for the study.	In summary, a demanding lifestyle characterized by a high amount of time pressure can lead to a shorter window of opportunity for the utilization of energy conservation measures in the building.
	Personal factors	Income, age, gender, skill, and method used to reduce energy usage, as well as education and		

Table 4 (cont). Reviewed studies on the factors influencing the implementations of building energy-efficiency practice

Sources	Features	Factors	Methodology	Conclusion
Richerzhagen et al., 2008 [93]	The following five issues were identified: i. A cluster of residing individuals ii. Society, life style and attitude. iii. Economic considerations. iv. Awareness, information, and knowledge. v. Legal structure and implementation.	awareness The corporate structure, regulation, and economic variables were recognized as the most powerful and critical aspects influencing building energy efficiency measures.	Questionnaires were employed for the study	The findings suggested that the essential factors for building energy conservation policy development, including the five identified elements, needed to be enhanced.
Yao, 2010 [23]	The study identified seven factors: i. Governmental regulation ii. Design standards iii. Building quality iv. Design quality v. Energy-efficient materials vi. Occupant behavior.	The most important aspects are government oversight, construction quality, and design specifications.	“Decision-Making Trial and Evaluation Laboratory Method”	The findings suggest that the most important criteria to assure the utilization of energy-efficient building techniques are government supervision, design standards, and construction quality.
Fatma, et, al., 2023 [94]	This focused on i. Challenges ii. Motivations iii. Recommendations iv. Futures pathways	These include carbon mitigations, reducing energy use improving building energy performances	Systematic review	Established a rigorous framework for government agencies and other relevant stockholders using the recent literatures as benchmark for implementing for proper energy efficiency in sustainable buildings.
Akram et, al., 2022 [95]	This mainly concerned with i. Fossil energy effects on buildings ii. Exploring other alternative sources of energy	Minimizing the usage of energy in Commercial and residential buildings	Reviewing energy policies and energy best practices	The research will assist relevant stockholders in advocating sustainable and green building through implementation other sources of energy for usage in buildings
Alawneh et, al., 2018 [96]	Achieving UN sustainable goal of i. Energy efficiency in green building ii. And water contribution assessment	Water efficiency, energy standards, and atmosphere standards in green buildings	Quantitative method was employed using structured questionnaire	Comprehensive Contribution to Development Index (CCDI) was proposed as reliable tools of examining the water and energy efficiency in green buildings in Jordan
Shareelna, 2021 [97]	This attempted to i. Balancing the demand and supply of energy in green buildings ii. Optimize the consumption through the advocate of green building energy	Improving annual cooling and lighting systems in existing buildings	Analytical approach of benefit transfer method	Creating sustainable future roadmap for the optimizing energy usages in Malaysia's housing.
Liu et, al., 2014 [98]	Analyzed the energy efficiency technology application on green building of china	Evaluating and Improving energy efficiency in green buildings	Cost-benefit analysis on green building technology	The research found out that power price is the most sensitive factor, followed by unit increase and lifetime of the building as the most parameters influencing cost of green building technology

be among the major hurdles to the adoption of energy-efficient policies [80, 81]. Quantifying and communicating the economic advantages of these measures can be difficult, and the need to provide evidence of benefits can decrease the return on investment [67, 82]. To overcome these barriers, a public guarantee mechanism may be an effective solution, as it would alleviate monetary risk and make it more attractive for institutional finances to invest in energy-efficient projects for households with low and middling incomes [19, 83]. Moreover, the lack of financing is also a primary contributor to these barriers [45, 84, 85] and manufacturers often face significant major investments and costs related to mass barriers of production caused by limited access to adequate capital [84, 86]. Furthermore, severe controls that limit access to funds, even when money is available on normal models, aggravate the problem [62, 87].

In addition to the barriers discussed earlier, several other impediments to the adoption of energy-efficient building practices have been explored by previous studies, providing valuable insights into the field. Some of these studies are summarized Table 3.

5. FACTORS INFLUENCING THE IMPLEMENTATION OF ENERGY EFFICIENT BUILDING PRACTICES

Three main factors have been identified by previous studies as the main influencers towards incorporating energy-efficient building techniques: occupant behavior, building characteristics, equipment, and technologies [21]. Building features such as orientation, design, window glazing, insulation, and materials all have a part in influencing energy usage [55]. In addition to that, heat recuperation, thermal energy storage, evaporative cooling, and adjustable air system are other major contributors to energy efficiency [18]. Occupant behavior, including the use of smart meters, smart grids, and control access, also plays a crucial role in determining energy consumption [86]. However, it is crucial to highlight that building attributes alone cannot ensure the optimal approach to designing a structure because it may be dependent on other aspects [6]. Additionally, economic and environmental benefits are not always considered in energy-efficient design solutions, also significant difficulties still exist in terms of cost-effectiveness [6]. As such, interventions aimed at changing occupants' behavior offer a relatively low-cost and simple solution to enhance energy efficiency [89]. These interventions may include technological updates, building service systems, and education to change their attitudes toward energy efficiency [6]. Therefore, technological updates, building service systems, and interventions to change occupant behavior should be considered as energy performance benchmarking to help occupants make smart decisions [6]. Table 4 bring together key insights from previous studies and presents a comprehensive outline of the numerous aspects that play important role in the implementation of energy-efficient building techniques and practices.

6. CONCLUSION

This study provides a thorough review of the various factors that influence the use of energy-efficient building practices, and the issues related to these factors, including barriers to implementation. The majority of reviewed studies focused on examining the impacts of energy efficiency using a questioner survey and decision-making trial and assessment laboratory technique. This study also highlighted that, government supervision, awareness, design standards, construction quality, and Energy Star materials are among the most significant factors influencing the building energy savings practice. Hence, both the government and construction stakeholders' roles are vital to promoting energy efficiency programs, standardizing building codes, and providing incentives for energy-efficient buildings. It is pertinent to remember, that cost-effectiveness is often one of the primary considerations in energy efficiency practices. Furthermore, precise numerical analytical findings are not always feasible to validate under realistic conditions [6]. To achieve this and provide alternative solutions for building owners, it is essential to have awareness, information, proper policy implementation, and other incentive programs. Therefore, by enhancing energy-efficient buildings with relatively low costs and simple construction procedures, the implementation of energy-efficient building practices can be made easy and can be useful for both existing and new buildings.

7. RECOMMENDATIONS

Removing barriers, as well as addressing the interplay of obstacles to the operation of energy-efficient building practices, are both essential and necessary. Possible suggestions for addressing these barriers include the following:

- To improve energy efficiency, it is essential to carry out local energy audit programs in buildings. This will make it easier to find areas that need improvements and create energy-saving initiatives. Additionally, regular monitoring and reporting of energy consumption can help to track progress and identify additional opportunities for savings [21].
- To increase energy efficiency awareness among residents, it is vital to involve the media in educating the public about environmental issues and energy conservation [46]. This can include public service announcements, news articles, and educational campaigns to promote energy-saving behaviors and technologies [24].
- It is critical to disseminate innovative technologies that use renewable resources throughout the world in order to increase energy efficiency. This will encourage the use of alternative energy methods and lessen reliance on fossil fuels [38]. Furthermore, in order to maintain the efficacy and cost of green energy sources, it is essential to encourage research and development of new solutions [13].
- To overcome financial hurdles to energy efficiency, it is critical to conduct research and form cooperation with institutions and international organizations [35].

This can include grants, low-interest loans, and tax incentives for energy-efficient upgrades. Additionally, financing options such as energy performance contracting (EPC) can also be considered.

- To reduce transaction costs, it is advisable to use marketplace-based regulations such as energy performance contracting (EPC). EPCs have been shown to have significant financial benefits and can be used to pay for energy efficiency measures. Additionally, implementing policies such as cap-and-trade systems or carbon pricing can also help to reduce transaction costs and incentivize energy efficiency.
- To ensure the effective execution of energy efficiency programs, it is crucial to involve all stakeholders, including individuals and institutions. This will help to build support for energy efficiency measures and to overcome any obstacles that may arise. Additionally, involving community members and local organizations can help to build grassroots support for energy efficiency efforts and increase participation in programs and initiatives. Furthermore, it is essential to consider the cultural and societal implications of energy efficiency, as different communities may have different needs and preferences.

DATA AVAILABILITY STATEMENT

The author confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

REFERENCES

- [1] K. Amasyali, and N. M. El-Gohary, "A review of data-driven building energy consumption prediction studies," *Renewable and Sustainable Energy Reviews*, Vol. 81, pp. 1192–1205, 2018. [\[CrossRef\]](#)
- [2] U. Berardi, "A cross-country comparison of the building energy consumptions and their trends," *Resources, Conservation and Recycling*, Vol. 123, pp. 230–241, 2017. [\[CrossRef\]](#)
- [3] T. Hong, C. Koo, J. Kim, M. Lee, and K. Jeong, "A review on sustainable construction management strategies for monitoring, diagnosing, and retrofitting the building's dynamic energy performance: Focused on the operation and maintenance phase," *Applied Energy*, Vol. 155, 671–707, 2015. [\[CrossRef\]](#)
- [4] D. Yan, T. Hong, B. Dong, A. Mahdavi, S. D'Oca, I. Gaetani, and X. Feng, "IEA EBC Annex 66: Definition and simulation of occupant behavior in buildings," *Energy and Buildings*, Vol. 156, pp. 258–270, 2017. [\[CrossRef\]](#)
- [5] M. A. McNeil, N. Karali, and V. Letschert, "Forecasting Indonesia's electricity load through 2030 and peak demand reductions from appliance and lighting efficiency," *Energy for Sustainable Development*, Vol. 49, pp. 65–77, 2019. [\[CrossRef\]](#)
- [6] S. Chen, G. Zhang, X. Xia, S. Setunge, and L. Shi, "A review of internal and external influencing factors on the energy efficiency design of buildings," *Energy and Buildings*, Vol. 216, Article 109944, 2020. [\[CrossRef\]](#)
- [7] M. Killian, and M. Kozek, "Ten questions concerning model predictive control for energy-efficient buildings," *Building and Environment*, Vol. 105, pp. 403–412, 2016. [\[CrossRef\]](#)
- [8] A. Fouquier, S. Robert, F. Suard, L. Stéphan, A. Jay, "State of the art in building modeling and energy performance prediction: A review," *Renewable and Sustainable Energy Reviews*, Vol. 23, pp. 272–288, 2013. [\[CrossRef\]](#)
- [9] Y. Guo, J. Wang, H. Chen, G. Li, J. Liu, C. Xu, R. Huang, and Y. Huang, "Machine learning-based thermal response time ahead energy demand prediction for building heating systems," *Applied Energy*, Vol. 221, pp. 16–27, 2018. [\[CrossRef\]](#)
- [10] P. Hernandez, X. Oregi, S. Longo, and M. Cellura, "Life-cycle assessment of buildings," in *Handbook of Energy Efficiency in Buildings*, 2019, pp. 207–261. [\[CrossRef\]](#)
- [11] M. G. Patterson, "What is energy efficiency?," *Energy Policy*, Vol. 24(5), pp. 377–390, 1996. [\[CrossRef\]](#)
- [12] J. Sousa, "Energy simulation software for buildings: review and comparison," *Information Technology for Energy Applications*, pp. 6–7, 2012. [\[CrossRef\]](#)
- [13] Z. N. Zhao, H. M. Zhang, Y. F. Ding, and L. Y. Shen, "Analysis on the Influencing Factors of Building Energy Consumption—A Southwest China Case Study," in *Proceedings of the 21st International Symposium on Advancement of Construction Management and Real Estate*, K. Chau, I. Chan, W. Lu, and C. Webster, Eds. Springer, Singapore, 2018. [\[CrossRef\]](#)
- [14] L. Gustavsson, and A. Joelsson, "Energy conservation and conversion of electrical heating systems in detached houses," *Energy and Buildings*, Vol. 39(6), pp. 717–726, 2007. [\[CrossRef\]](#)
- [15] A. Trianni, and E. Cagno, "Dealing with barriers to energy efficiency and SMEs: Some empirical evidence," *Energy*, Vol. 37(1), pp. 494–504, 2012. [\[CrossRef\]](#)
- [16] Y. A. Çengel, "Energy efficiency is an inexhaustible energy resource with perspectives from the U.S. and Turkey," *International Journal of Energy Research*, Vol. 35(2), pp. 153–161, 2011. [\[CrossRef\]](#)
- [17] E. Agharese, U. Etiosa, A. Matthew, O. G. Ogbemudia, P. U. Osazee, and G. O. Ose, "Community Research and Development Centre," Article 6, 2009.

- [18] I. U. Hussaini, and N. H. Abdul Majid, "Energy development in Nigeria and the need for strategic energy efficiency practice scheme for the residential building sector," *Management of Environmental Quality: An International Journal*, Vol. 26(1), pp. 21–36, 2015. [CrossRef]
- [19] M. Economidou, V. Todeschi, and P. Bertoldi, "Accelerating energy renovation investments in buildings," 2019.
- [20] S. O. Oyedepo, "Efficient energy utilization as a tool for sustainable development in Nigeria," *Int J Energy Environ Engineering*, Vol. 3(11), 2012. [CrossRef]
- [21] A. Allouhi, Y. El Fouih, T. Kousksou, A. Jamil, Y. Zeraoui, and Y. Mourad, "Energy consumption and efficiency in buildings: current status and future trends," *Journal of Cleaner Production*, Vol. 109, pp. 118–130, 2015. [CrossRef]
- [22] O. C. Chibuisi, "Energy efficiency," *Global Scientific Journals*, Vol. 7(4), pp. 2320–9188, 2019.
- [23] J. Yao, "Analysis of influencing factors of building energy efficiency based on the DEMATEL method," in *2010 International Conference on Optics, Photonics, and Energy Engineering (OPEE)*, 2010. [CrossRef]
- [24] I. C. Ezema, and S. A. Maha, "Energy efficiency in high-rise office buildings: An appraisal of its adoption in Lagos, Nigeria. *IOP Conference Series: Earth and Environmental Science*, Vol. 1054, Article 012037, 2022. [CrossRef]
- [25] S. Nandi, and R. K. Bose, "The Imperative of Efficient Energy Use in Cities: Analytical Approaches and Good Practices," in R. K. Bose, Ed., *Energy Efficient Cities: Assessment Tools and Benchmarking Practices*, The World Bank, Washington D.C, 2010, pp. 1–19.
- [26] Global Energy Assessment, "Global Energy Assessment - Toward a Sustainable Future," Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria, 2012.
- [27] B. Kiss, "Building Energy Efficiency - Policy, learning, and technology change," *International Institute for Industrial Environmental Economics*, Lund University, 2013.
- [28] S. Mitsushima, B. Gollas, and V. Hacker, "Introduction," in *Fuel Cells and Hydrogen*, V. Hacker and S. Mitsushima, Eds. Elsevier, 2018, pp. 1–13. [CrossRef]
- [29] Y. Demirel, "Energy Conservation," in *Comprehensive Energy Systems*, I. Dincer, Ed. Elsevier, 2018, pp. 45–90. [CrossRef]
- [30] E. Spentzou, "Refurbishment of apartment buildings in the Mediterranean Region for natural ventilation: implications for building design," [Doctorial dissertation], Loughborough University, 2015.
- [31] W. Nijs, D. Tarvydas, and A. Toleikyte, "EU challenges of reducing fossil fuel use in buildings – The role of building insulation and low-carbon heating systems in 2030 and 2050," *EUR 30922 EN*, Publications Office of the European Union, Luxembourg, 2021.
- [32] Wikipedia, "Household," Available at: <https://en.wikipedia.org/wiki?cv=1&curid=725893> Accessed on Jan 21, 2023.
- [33] M. Lackner, "Energy Efficiency: Comparison of Different Systems and Technologies," in *Handbook of Climate Change Mitigation and Adaptation*, W. Y. Chen, T. Suzuki, and M. Lackner, Eds. Springer, 2017, pp. 1–15. [CrossRef]
- [34] P. A. Østergaard, N. Duic, Y. Noorollahi, H. Mikulcic, and S. Kalogirou, "Sustainable development using renewable energy technology," *Renewable Energy*, vol. 146, pp. 2856–2864, 2020.
- [35] Y. M. Wei and H. Liao, "Residential Energy Consumption," in *Energy Economics: Energy Efficiency in China*. Springer, 2016, pp. 41–60. [CrossRef]
- [36] [F. Kern, P. Kivimaa, and M. Martiskainen, "Policy packaging or policy patching? The development of complex energy efficiency policy mixes," *Energy Research & Social Science*, Vol. 23, pp. 11–25, 2017. [CrossRef]
- [37] G. O. Unachukwu, "Energy efficiency measures investigation in cement company: BCC Case study," *Nigerian Journal of Renewable Energy*, Vol. 10(1&2), pp. 85–92, 2003. [CrossRef]
- [38] A. Santangelo, and S. Tondelli, "Consumer Behavior in Building Energy Use," in *Affordable and Clean Energy. Encyclopedia of the UN Sustainable Development Goals*, W. Leal Filho, A. Marisa Azul, L. Brandli, A. Lange Salvia, and T. Wall, Eds. Springer, 2021, pp. 1–20. [CrossRef]
- [39] I. U. Hussaini, "Household energy efficiency practice in Bauchi," [Doctorial dissertation], Kulliyah of Architecture and Environmental Design, International Islamic University Malaysia, Kuala Lumpur, 2012.
- [40] J. Kellett, "Community-based energy policy: A practical approach to carbon reduction," *Journal of Environmental Planning and Management*, Vol. 50(3), pp. 381–396, 2007.
- [41] T. Fleiter, J. Schleich, and P. Ravivanpong, "Adoption of energy-efficiency measures in SMEs-An empirical analysis based on energy audit data from Germany," *Energy Policy*, Vol. 51, pp. 863–875, 2012. [CrossRef]
- [42] J. Zheng, "Urban Residential Energy Efficiency - Technology Optimization and Behaviour Change: Case study on social housing in Darmstadt, Germany," Darmstadt, Technische Universität, 2019. Available at: <https://tuprints.ulb.tu-darmstadt.de/id/eprint/9455>. Accessed on Feb 21, 2023.
- [43] FMPWH-NESP, "Building Energy Efficiency Guideline for Nigeria (BEEG)," released by the Federal Ministry of Power, Works and Housing, Abuja, 2016. Available at: https://energypedia.info/images/c/c7/Building_Energy_Efficiency_Guideline_for_Nigeria_2016.pdf. Accessed on Jan 08, 2023.
- [44] L. A. Bugenings, and A. Kamari, "Bioclimatic Architecture Strategies in Denmark: A Review of Current and Future Directions," *Buildings*, Vol. 12(2), Article 224, 2022. [CrossRef]

- [45] SDG, "Accelerating SDG7 Achievement Policy Briefs In Support Of The First SDG7 Review At The UN High-Level Political Forum 2018," 2018. Available at: https://sustainabledevelopment.un.org/content/documents/18041SDG7_Policy_Brief.pdf?cv=1. Accessed on Mar 06, 2023.
- [46] G. Nair, K. Mahapatra, and L. Gustavsson, "Implementation of energy-efficient windows in Swedish single-family houses," *Applied Energy*, Vol. 89(1), pp. 329–338, 2012. [CrossRef]
- [47] M. Hyland, R. Lyons, and S. Lyons, "The value of domestic building energy efficiency - evidence from Ireland," *Energy Economics*, 2012. University of Oxford Department of Economics Working Paper No. 614. [CrossRef]
- [48] American Council for an Energy Efficiency Economy (ACEEE), "Energy efficiency job creation: Real world experience," 2012. Available at: <https://www.aceee.org/files/pdf/white-paper/energy-efficiency-job-creation.pdf> Accessed on Oct 31, 2023.
- [49] IEA, "Accelerating energy efficiency: What governments can do now to deliver energy savings," IEA, Paris, 2022. Available at: <https://www.iea.org/commentaries/accelerating-energy-efficiency-what-governments-can-do-now-to-deliver-energy-savings>. Accessed on Feb 03, 2023.
- [50] B. Lee, "Building Energy Simulation and the Design of Sustainable and Resilient Buildings," in *Sustainable Real Estate*, T. Walker, C. Krosinsky, L. N. Hasan, and S. D. Kibsey, Eds. Palgrave Macmillan, pp. 177–193, 2019.
- [51] D. A. Collins, "A Study of the Barriers and Drivers for Green Leased Offices in Norway," *Norwegian University of Science and Technology*, 2019.
- [52] F. Squinazi, "Managing indoor air quality to protect occupant health," *Field Actions Science Reports*, Special Issue 21, pp. 8–13, 2020.
- [53] K. M. J. Barasa, and O. O. Akanni, "Sustainable Energy Transition for Renewable and Low Carbon Grid Electricity Generation and Supply," *Frontiers in Energy Research*, Vol. 9, Article 743114, 2022. [CrossRef]
- [54] B. Mills, and J. Schleich, "Residential energy-efficient technology adoption, energy conservation, knowledge, and attitudes: An analysis of European countries," *Energy Policy*, Vol. 49, pp. 616–628, 2012. [CrossRef]
- [55] D. E. Marasco, and C. E. Kontokosta, "Applications of machine learning methods to identifying and predicting building retrofit opportunities," *Energy and Buildings*, Vol. 128, pp. 431–441, 2016. [CrossRef]
- [56] V. Eswarlal, "A sustainable supply chain study of the Indian bioenergy sector," *Aston University*, 2014. Available at: <https://publications.aston.ac.uk/id/eprint/22337/1/Studentthesis-2014.pdf?cv=1> Accessed on April 08 2023.
- [57] S. Yigit, and B. Ozorhon, "A Simulation-Based Optimization Method for Designing Energy Efficient Buildings," *Energy and Buildings*, Vol. 178, pp. 216–227, 2018. [CrossRef]
- [58] E. Atam, "Current software barriers to advanced model-based control design for energy-efficient buildings," *Renewable and Sustainable Energy Reviews*, Vol. 73, pp. 1031–1040, 2017. [CrossRef]
- [59] J. L. Sousa, A. G. Martins, and H. Jorge, "Dealing with the paradox of energy efficiency promotion by electric utilities," *Energy*, Vol. 57, pp. 251–258, 2013. [CrossRef]
- [60] S. Attia, L. Beltrán, A. Herde, and J. Hensen, "Architect friendly": a comparison of ten different building performance simulation tools," *Eleventh International IBPSA Conference Glasgow, Scotland*, 27–30, 2009. Available at: https://orbi.uliege.be/bitstream/2268/167578/1/BS09_0204_211.pdf Accessed on Jan 01 2023.
- [61] V. S. K. V. Harish, and A. Kumar, "A review of modeling and simulation of building energy systems," *Renewable and Sustainable Energy Reviews*, Vol. 56, pp. 1272–1292, 2016. [CrossRef]
- [62] M. Suzuki, "Identifying roles of international institutions in clean energy technology innovation and diffusion in the developing countries: matching barriers with roles of the institutions," *Journal of Cleaner Production*, Vol. 98, pp. 229–240, 2015. [CrossRef]
- [63] M. Seddiki, A. Bennadji, and M. Tehami, "Barriers to the adoption of energy efficiency measures in Mostaganem, Algeria," *Journal of Construction in Developing Countries*, Vol. 25(2), pp. 39–61, 2020. [CrossRef]
- [64] A. I. Mu'azu, "Scenario of Energy Consumption of Office Buildings in Abuja, Nigeria," *International Journal of Science and Advanced Technology*, Vol. 2, Article 1546658, 2012.
- [65] K.-H. Chain and C. Yeo, "Overcoming energy efficiency barriers through systems approach—A conceptual framework," *Energy Policy*, Vol. 46, pp. 460–472, 2012. [CrossRef]
- [66] G. Nair, L. Gustavsson, and K. Mahapatra, "Factors influencing energy efficiency investments in existing Swedish residential buildings," *Energy Policy*, Vol. 38(6), pp. 2956–2963, 2010. [CrossRef]
- [67] A. Bagaini, F. Colelli, E. Croci, and T. Molteni, "Assessing the relevance of barriers to energy efficiency implementation in the building and transport sectors in eight European countries," *The Electricity Journal*, Vol. 33(8), Article 106820, 2020. [CrossRef]
- [68] E. Igharehbaghi, Q. K. Qian, F. M. Meijer, and H. J. Visscher, "Unravelling Dutch homeowners' behaviour towards energy efficiency renovations: What drives and hinders their decision-making?" *Energy Policy*, Vol. 129, pp. 546–561, 2019. [CrossRef]
- [69] N. Labanca, and P. Bertoldi, "Beyond energy efficiency and individual behaviours: policy insights from social practice theories," *Energy Policy*, Vol. 115, pp. 494–502, 2018. [CrossRef]
- [70] T. Hong, D. Yan, S. D'Oca, and C. Chen, "Ten questions concerning occupant behavior in buildings: The big picture," *Building and Environment*, Vol. 114, pp. 518–530, 2017. [CrossRef]

- [71] R. R. Kumar, and A. Kumar, "Adoption of electric vehicle: A literature review and prospects for sustainability," *Journal of Cleaner Production*, Vol. 253, Article 119911, 2020. [CrossRef]
- [72] B. F. Balvedi, E. Ghisi, and R. Lamberts, "A review of occupant behaviour in residential buildings," *Energy and Buildings*, Vol. 174, pp. 495–505, 2018. [CrossRef]
- [73] S. Hu, D. Yan, E. Azar, and F. Guo, "A systematic review of occupant behavior in building energy policy," *Building and Environment*, Article 106807, 2020. [CrossRef]
- [74] O. Lah, "The barriers to low-carbon land-transport and policies to overcome them," *European Transport Research Review*, Vol. 7(1), Article 5, 2015. [CrossRef]
- [75] C. Cattaneo, "Internal and external barriers to energy efficiency: which role for policy interventions?" *Energy Efficiency*, Vol. 12, pp. 1293–1311, 2019. [CrossRef]
- [76] S. D'Oca, A. Ferrante, C. Ferrer, R. Perneti, A. Gralka, R. Sebastian, and P. Op 't Veld 1 "Technical, Financial, and Social Barriers and Challenges in Deep Building Renovation: Integration of Lessons Learned from the H2020 Cluster Projects," *Buildings*, Vol. 8(12), p. 174, 2018. [CrossRef]
- [77] I. L. Wong, and E. Krüger, "Comparing energy efficiency labelling systems in the EU and Brazil: Implications, challenges, barriers and opportunities," *Energy Policy*, Vol. 109, pp. 310–323, 2017. [CrossRef]
- [78] S. Langlois-Bertrand, M. Benhaddadi, M. Jegen, and P.-O. Pineau, "Political-institutional barriers to energy efficiency," *Energy Strategy Reviews*, Vol. 8, pp. 30–38, 2015. [CrossRef]
- [79] L. Castellazzi, P. Bertoldi, and M. Economidou, "Overcoming the split incentive barrier in the building sector," Available at: <https://ec.europa.eu/jrc/en> Accessed on Jan 5, 2023.
- [80] P. Thollander, J. Palm, and P. Rohdin, "Categorizing barriers to energy efficiency: an interdisciplinary perspective," *Energy Efficiency*, pp. 49–63, 2010. [CrossRef]
- [81] M. E. Biresselioglu, M. Demirbag Kaplan, and B. K. Yilmaz, "Electric mobility in Europe: A comprehensive review of motivators and barriers in decision making processes," *Transportation Research Part A: Policy and Practice*, Vol. 109, pp. 1–13, 2018. [CrossRef]
- [82] J. Painuly, "Barriers to renewable energy penetration; a framework for analysis," *Renewable Energy*, Vol. 24(1), pp. 73–89, 2001. [CrossRef]
- [83] S. Sorrell, E. O'Malley, J. Schleich, and S. Scott "Standing on a burning platform: barriers to energy efficiency in the U.K. brewing industry," *The Economics of Energy Efficiency: Barriers to Cost-Effective Investment*, Cheltenham: Edward Elgar, 2004. Available at: <https://ideas.repec.org/b/elg/ee-book/2607.html> Accessed on Apr 12, 2023.
- [84] N. H. Ravindranath, and P. Balachandra, "Sustainable bioenergy for India: Technical, economic and policy analysis," *Energy*, Vol. 34(8), pp. 1003–1013, 2009. [CrossRef]
- [85] S. Thorne, "Towards a framework of clean energy technology receptivity," *Energy Policy*, Vol. 36(8), pp. 2831–2838, 2008. [CrossRef]
- [86] A. Jagadeesh, "Wind energy development in Tamil Nadu and Andhra Pradesh, India Institutional dynamics and barriers—A case study," *Energy Policy*, Vol. 28(3), pp. 157–168, 2000. [CrossRef]
- [87] C. Karakosta, H. Doukas, and J. Psarras, "Technology transfer through climate change: Setting a sustainable energy pattern," *Renewable and Sustainable Energy Reviews*, Vol. 14(6), pp. 1546–1557, 2010. [CrossRef]
- [88] E. M. Rogers, "Diffusion of Innovations," New York: The Free Press; 2003.
- [89] D. Espejel-Blanco, J. A. Hoyo-Montaña, J. Arau, G. Valencia-Palomo, A. García-Barrientos, H. Ricardo Hernández-De-León, L. Camas-Anzueto, "HVAC Control System Using Predicted Mean Vote Index for Energy Savings in Buildings," *Buildings*, Vol. 12, Article 38, 2022. [CrossRef]
- [90] E. Annunziata, F. Rizzi, and M. Frey, "Enhancing energy efficiency in public buildings: The role of local energy audit programs," *Energy Policy*, Vol. 69, pp. 364–373, 2014. [CrossRef]
- [91] Q. Cui, H. Kuang, C. Wu, and Y. Li, "The changing trend and influencing factors of energy efficiency: The case of nine countries," *Energy*, Vol. 64, pp. 1026–1034, 2014. [CrossRef]
- [92] C. Richerzhagen, T. von Frieling, N. Hansen, A. Minnaert, N. Netzer, and J. Rußbild, "Energy efficiency in buildings in China: Policies, barriers and opportunities," (*DIE Studies*, 41), 2008.
- [93] J. Chillayil, M. Suresh, V. PK, S. K. Kottayil, "Is imperfect evaluation a deterrent to adoption of energy audit recommendations?," *International Journal of Productivity and Performance Management*, Vol. 71(4), pp. 1385–1406, 2022. [CrossRef]
- [94] F. S. Hafez, B. Sa'di, M. Safa-Gamal, Y. H. Taufiq-Yap, M. Alrifay, M. Seyedmahmoudian, A. Stojcevski, B. Horan, and S. Mekhilef, "Energy Efficiency in Sustainable Buildings: A Systematic Review with Taxonomy, Challenges, Motivations, Methodological Aspects, Recommendations, and Pathways for Future Research," *Energy Strategy Reviews*, vol. 45, Article 101013, 2023. [CrossRef]
- [95] M. W. Akram, M. F. Mohd Zublie, M. Hasanuzzaman, and N. Abd Rahim, "Global prospects, advance technologies and policies of energy-saving and sustainable building systems: A review," *Sustainability*, Vol. 14, Article 1316, 2022. [CrossRef]
- [96] R. Alawneh, F. E. Mohamed Ghazali, H. Ali, and M. Asif, "Assessing the contribution of water and energy efficiency in green buildings to achieve United Nations Sustainable Development Goals in Jordan," *Building and Environment*, Vol. 146, pp. 119–132, 2018. [CrossRef]
- [97] S. S. A. Azis, "Improving present-day energy savings among green building sector in Malaysia using benefit transfer approach: Cooling and lighting loads," *Renewable and Sustainable Energy Reviews*, Vol. 137, Article 110570, 2021. [CrossRef]
- [98] Y. Liu, X. Guo, and F. Hu, "Cost-benefit analysis on green building energy efficiency technology application: A case in China," *Energy and Buildings*, Vol. 82, pp. 37–46, 2014. [CrossRef]



Review Article

Sustainable spatial strategies for mitigating air pollution in quick commerce environments

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ARTICLE INFO

Article history

Received: 28 September 2023

Revised: 01 November 2023

Accepted: 03 November 2023

Key words:

Air pollution; Greenhouse gases, Packaging waste, Quick Commerce; Sustainable consumption

ABSTRACT

This paper reviewed various studies on the impact of quick-commerce distribution services on the environment and local communities, with a particular focus on air pollution and increased packaging waste due to the increase in quick-commerce consumption. A systematic literature review was conducted using Web of Science, Google Scholar, and Scopus to comprehensively investigate and summarise the characteristics of quick commerce distribution, the impact of frequent logistics transport on air pollution, and the increase in packaging waste due to the increase in online shopping demand. Previous studies have mainly addressed the growth characteristics of quick commerce distribution services with the emergence of quick commerce. The results of this study show that quick-commerce distribution services are indeed associated with increased traffic due to frequent transport, which contributes to greenhouse gas emissions and traffic congestion in cities. In addition, due to the nature of quick-commerce consumption, packaging waste is also increasing due to excessive use of packaging materials for freshness and safe delivery. Therefore, this study suggests sustainable consumption behaviour using local shopping malls and private spaces to minimize environmental pollution in the era of changed distribution services.

Cite this article as: Son E, Kwon KH. Sustainable spatial strategies for mitigating air pollution in quick commerce environments. Environ Res Tec 2024;7(1)131–139.

INTRODUCTION

The rapid development of technology and the widespread adoption of personal mobile phones have significantly expanded the accessibility of various goods and services for online consumption. This shift has led to an increasing number of people transitioning to online shopping, driven by the convenience of unrestricted access, reduced purchasing effort, and the flexibility of time and location [1–3]. The growth of the online shopping market offers advantages not only to consumers but also to companies, enabling easier product promotion and distribution to a larger customer base while providing valuable insights into consumer preferences through purchase histories [4].

In the United States, approximately one-third of Internet users engage in online shopping at least once a week. In 2017, online shopping transactions in the U.S. amounted to \$448.3 billion, accounting for 8.8% of all retail transactions, with an annual growth rate of approximately 15% over the past five years [5]. Furthermore, the COVID-19 pandemic catalyzed a paradigm shift towards online shopping, as offline stores faced temporary closures during lockdowns. The contactless nature of online shopping made it an attractive option for consumers, and businesses reinforced their online presence [6, 7]. The post-pandemic surge in the online shopping market has been remarkable. According to a survey by Nint, Inc., Japan's seven major online trading markets witnessed a 7% increase in sales in January

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2020, followed by 13% in February and 14% in March compared to the same months the previous year. Notably, sales of medical products surged, and while offline retail sales worldwide are projected to decline by 19% in 2021, online retail sales are expected to grow by 19% [8].

In the fast-paced modern world of 2023, quick commerce has emerged as a prominent consumer behavior trend. Quick commerce offers consumers the convenience of rapidly placing orders and receiving doorstep deliveries within a short timeframe [9]. Consumers are willing to pay extra for expedited home deliveries, driven by the desire for delivery time flexibility [10]. Although companies have successfully tackled the logistical challenges of achieving fast delivery by establishing densely packed warehouses and continuous operation, this convenience also comes with drawbacks, including increased environmental impact associated with frequent deliveries [11]. An exclusive focus on the convenience of quick commerce may result in underestimating the emissions and environmental consequences of online delivery and quick-commerce distribution. Frequent deliveries, particularly in the context of groceries, contribute significantly to air pollution through a 125% increase in food-related vehicle miles traveled (VMT). While reducing distribution frequency can mitigate VMT, it may come at the expense of revenue. Considering that all delivery vehicles currently rely on internal combustion engines, the environmental implications of frequent online grocery deliveries encompass traffic congestion, emissions, and energy consumption [12]. Frequent delivery consumption is a behavioral factor exacerbating air pollution, further affecting daily air quality fluctuations influenced by both anthropogenic emissions and atmospheric conditions, which determine the concentration and dispersion of pollutants [13].

Consumption practices that contribute to air pollution create a cycle of deteriorating air quality and heightened waste emissions. This study aims to investigate the air pollution implications of distribution services associated with quick commerce, with a specific focus on the surge in packaging waste resulting from delivery services. We present a synthesis of recent research findings in this area and, based on these insights, propose sustainable consumption behaviors leveraging local shopping malls and personal spaces to mitigate environmental pollution.

MATERIALS AND METHODS

This review aims to update the current state of research with a focus on sustainable consumption using local commercial and personal spaces to reduce environmental pollution that contributes to climate change, noting that air pollution and packaging waste from quick-service retailing are on the rise. Below we describe in detail our search strategy, article selection methods, and data synthesis procedures.

Search Strategy

For this review, we searched six databases in the natural sciences, social sciences, environmental engineering, and

management and consumption, following PRISMA flow guidelines: PubMed, Scopus, Medline, ResearchGate, and Google Scholar, using the search terms (a) 'quick-service retail' and 'online shopping' (b) 'packaging waste' (c) 'transport' and 'air pollution'. Figure 1 is a flowchart showing the process of selecting studies for inclusion in this review.

Eligibility Criteria

Articles included in this review had to meet the eligibility criteria for this review, including selecting studies related to the characteristics of quick commerce distribution, types of air pollutants, frequent distribution services, online shopping, and packaging waste.

Screening and Data Extraction

Articles were included in the corpus if they (1) investigated the increase in distribution logistics due to quick commerce, (2) addressed the association between quick commerce distribution services and air pollution, (3) related to online shopping and packaging waste, (4) addressed the impact of online shopping on environmental pollution, (5) were peer-reviewed, and (6) were journal articles or conference presentations.

We excluded papers that (1) did not investigate the characteristics of quick commerce or online shopping, (2) did not investigate the link between retail logistics services and air pollution or environmental pollution, or (3) did not investigate online shopping and packaging waste.

Different types of articles were considered, including original articles, full-text articles, internet articles, summary reports, and series, and no restrictions were placed on publication date or language. Exclusion criteria included inaccessible full text, full text without raw data, inappropriate topic, and doctoral dissertations; these articles were retrieved through the ProQuest Dissertations and Theses global database.

Study Selection and Data Extraction

We used a literature review approach: a total of 297 references were selected using the PRISMA flowchart from the major journal search sites PubMed, Google Scholar, ResearchGate, Medline, and Scopus. This resulted in a total of 44 articles being selected. The PRISMA flowchart is shown in Figure 1.

3. ENVIRONMENTAL IMPACT OF QUICK COMMERCE CONSUMPTION

Air Pollution From Frequent Transport

Quick commerce is a sector characterized by the adept utilization of advanced technological solutions and intricate logistics systems, aimed at achieving the swift delivery of products mere hours or even minutes subsequent to their order placement. This paradigm centers its core objectives on expeditiousness and customer convenience, striving to furnish a shopping experience that is utterly seamless and devoid of friction [14]. The progression towards food

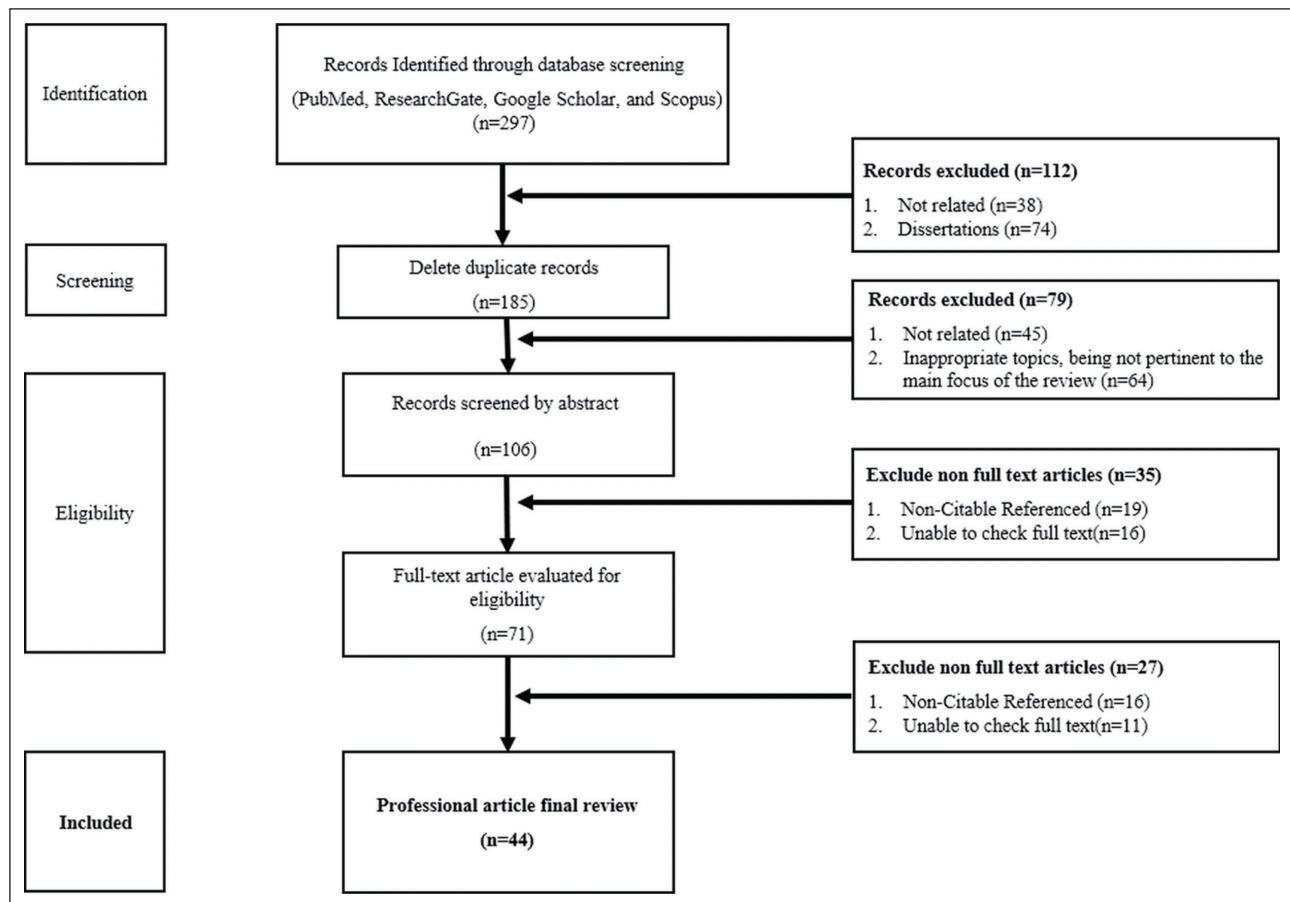


Figure 1. PRISMA flow chart for literature review search results.

e-commerce was facilitated through the assimilation of novel technologies, the emergence of innovative market participants that introduced heightened complexity and dynamism to the sector, and the cultivation of advanced logistical capabilities, exemplified by the advent of dark stores and micro-hubs. Quick commerce signifies the evolution of instantaneous delivery, now encompassing the entirety of the food and online shopping landscape. It is underpinned by an infrastructure of logistics micro-hubs, overseeing large-scale distribution, and exhibits a conspicuous reliance on transportation, characterized by the frequent movement of vehicles and the ensuing delivery workflows [15].

However, it is imperative to acknowledge the environmental ramifications and transportation intensiveness accompanying deliveries conducted through conventional means such as cars and gasoline-powered motorcycles, which emit significantly higher levels of greenhouse gases—approximately five to eleven times more—per delivery compared to their bicycle counterparts, particularly those confined to local shopping vicinities. This pronounced disparity in transport and greenhouse gas emissions underscores substantial policy considerations, particularly in light of the rapid global proliferation of such services [16].

According to a report published by the UK Department for Transport [17], the transportation sector constituted 27% of the total greenhouse gas emissions in the United Kingdom for the year 2019. Notably, heavy goods vehicles (HGVs)

and vans accounted for a substantial 35% of emissions within the transport sector. Figure 2 illustrates a noteworthy escalation in the mileage covered by HGVs and vans spanning from 1990 to 2019, predominantly attributable to the burgeoning e-commerce sector. Furthermore, the persistent expansion of the quick-commerce market and the upsurge in intracity home delivery distribution engender the ingress of trucks and lorries into urban areas, thereby precipitating adverse externalities such as heightened traffic congestion, amplified emissions, and increased pollution levels [18, 19].

One of the most pivotal domains within urban goods transportation pertains to the last-mile delivery, encompassing the multifaceted processes requisite for conveying goods from their point of origin, typically a retail store or a warehouse, to their ultimate destination, culminating in the final leg of the delivery chain [20, 21]. It is worth noting that last-mile logistics exercises a discernible influence on customer satisfaction levels, shapes consumer impulsive buying tendencies [22, 23], and exerts a positive impact on the loyalty metrics for e-commerce enterprises [24].

E-commerce undertakings are not without their ecological footprint, with environmental consequences stemming from packaging, labeling, transportation activities, energy consumption, and the transmission of information, all of which contribute to the generation of carbon emissions and associated costs [25]. Beyond environmental ramifications,

Countries	Energy development strategies and policy trends
Russia	Russia will reduce net greenhouse gas emissions by 60% from 2019 levels by 2050 and by 80% from 1990 levels, and achieve carbon neutrality by 2060.
Canada	Canada will ban new gas car sales in 2035 and aims for net-zero emissions by 2050.
China	China strives to reach the peak of carbon dioxide emissions by 2030 and strives to achieve carbon neutrality by 2060.
France	France will rely on renewables and nuclear power to achieve net-zero emissions by 2050
United Kingdom	The UK will reduce greenhouse gas emissions by 78% in 2035 compared with 1990 and will achieve a 100% clean carbon-free power supply in the power system by 2035.
United States	The United States seeks net-zero electricity sector emissions by 2035 and net-zero greenhouse gas emissions by 2050.

Figure 2. Changes in mileage and emissions from 1990 to 2019 (Gund, H.P. & Daniel, J. (2023). “Q-commerce or E-commerce? A systematic state of the art on comparative last-mile logistics greenhouse gas emissions literature review”. International Journal of Industrial Engineering and Operations Management).

the domain of e-commerce last-mile logistics significantly permeates into the economic and societal dimensions of sustainability [20], which encompasses the betterment and preservation of natural resources, economic vitality, and overall quality of life [26].

Increased Packaging Waste

The surge in food delivery services has experienced remarkable growth in recent years, notably catalyzed by the onset of the COVID-19 pandemic. A noteworthy transformation in consumer behavior unfolded, with the data reflecting a remarkable shift. In July 2019, a mere 20 percent of US consumers engaged in online grocery shopping. However, by June 2020, amidst the pandemic's aftermath, this figure surged to an unprecedented 80 percent, exemplifying the rapid expansion of the sector [8].

Fundamentally, packaging serves as the paramount means of safeguarding various products, encompassing a spectrum ranging from food items to electronics and manufactured goods, against potential damage. The principal role of product packaging revolves around the preservation of product integrity, ensuring that items are delivered in an optimal condition conducive to successful trade. This pivotal facet of product packaging concurrently facilitates the processes of transportation, handling, storage, and preservation [27]. In the context of food orders facilitated through quick commerce, the conspicuous characteristic of generating substantial packaging waste emerges as a salient concern. The packaging arsenal employed encompasses an array of elements, spanning from delivery packaging boxes to plastic containers, all aimed at averting food deformation or damage during transit. However, it is essential to underscore that the extensive use of plastics within this framework imposes a significant environmental burden. The

repercussions associated with greenhouse gas emissions (GHGs) and the production and consumption of plastics transcend national boundaries, exerting a global impact. This underscores the imperative of curbing current levels of plastic waste to address the urgent imperative of limiting global warming to below 1.5 °C [28].

Many quick commerce enterprises advocate the adoption of eco-friendly practices, including the utilization of paper tape for packaging and water-based ice packs for the delivery of frozen food. Nevertheless, these endeavors, while rooted in resource-conscious principles, are not entirely devoid of resource utilization and waste generation. Express delivery packaging predominantly incorporates recycled materials, but post-consumer packaging waste is subjected to only partial recycling efforts. Additionally, plastic packaging predominantly derives from recycled agricultural film, carrying residual chemical residues from pesticide applications, potentially posing health risks to industry personnel and consumers alike [29].

Notably, the multifaceted nature of express delivery amplifies its environmental footprint, prominently evident in the diverse array of packaging materials employed. For instance, research conducted by Fan et al. [30] elucidated the environmental burden imposed by express delivery packaging materials through a comprehensive life cycle assessment approach. Indeed, each express delivery order necessitates the deployment of a multitude of packaging components, encompassing corrugated and cardboard boxes, plastic and bubble wrap, adhesive tabs, polystyrene foam, and air blister fillers. Figure 3 graphs the growth of packaging waste from the 1990s to the 2020s based on China. While certain packaging materials, such as corrugated boxes, offer recyclability and reusability prospects, a significant proportion of packaging waste from shipping finds its way to municipal

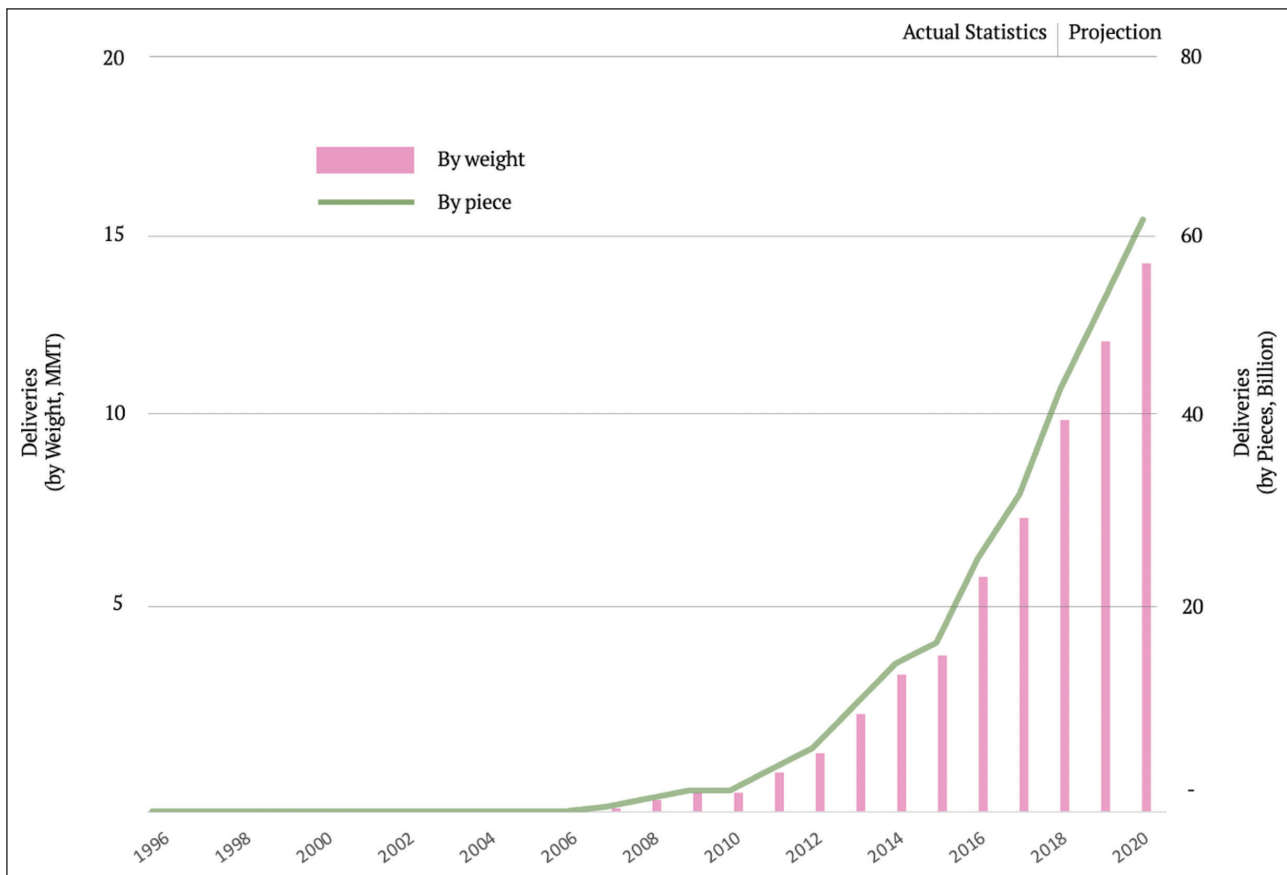


Figure 3. Total volume of express delivery packages and weight of packaging waste in China from 1996 to 2020 (Huabo Duan, Guanghan Song, Shen Qu, Xiaobin Dong, Ming Xu, Post-consumer packaging waste from express delivery in China, Resources, Conservation and Recycling, Volume 144, 2019, Pages 137–143).

solid waste (MSW) sites, where it either undergoes landfilling, incineration, or simply improper disposal. This is particularly concerning considering that a substantial portion of packaging waste comprises non-biodegradable materials such as PVC plastic, polyethylene plastic, expanded polystyrene plastic, and polyester plastic, thus underscoring the severe environmental consequences stemming from inadequate disposal practices [31]. The persistence of non-biodegradable materials, notably PVC, not only exacerbates environmental concerns but also presents challenges related to plastic waste marketability, emissions, and corrosion during thermal treatment. The prevalence of non-biodegradable plastics represents a pervasive issue, manifesting in landfills, roadside litter, and the infamous phenomenon of plastic pollution in aquatic ecosystems, commonly referred to as the “plastic soup” [29].

Food Security Inequalities Caused by Quick Commerce

The proliferation of food purchases through quick commerce channels is having a discernible impact on local commercial districts, underpinned by several key factors. Firstly, the global population is on a trajectory of continuous growth, necessitating an increased demand for food resources. While residents of developed megacities enjoy the convenience of swift access to a wide array of food options via quick commerce, many other areas remain underserved

by this burgeoning trend. Consequently, disparities in food security are exacerbated, posing a challenge to equitable access to sustenance [32]. Furthermore, the environmental footprint stemming from the rapid adoption of quick commerce food consumption systems in large urban centers is poised to escalate gradually, emphasizing the exigency of exploring alternative approaches to food provisioning. A pivotal strategy involves the mitigation of food wastage while ensuring a sufficient supply of food within local regions. This approach is geared towards ameliorating the associated environmental consequences [32].

Large cities, by their nature, furnish a conducive social milieu replete with novel opportunities for interaction, thereby fostering individual learning and personal development. However, the distribution of these opportunities among individuals varies considerably and tends to diverge over time, primarily contingent upon the city's size and the prevailing inequalities within its confines [33]. Analogously, disparities in food consumption patterns manifest, with discernible discrepancies in food security emerging between generations possessing easy online access and those bereft of such access or contending with the dominance of overheated quick commerce enterprises. These disparities may potentially precipitate challenges related to food availability and subsequently exert upward pressure on market food prices. Hence, it is incumbent upon the nation to pro-

actively attend to and strategize for the development of infrastructure and initiatives pertaining to various facets of the food system, encompassing arable land, water resources, agricultural crops, livestock, and fisheries [18]. Indeed, the burgeoning quick commerce consumption landscape is impinging on the vitality of local brick-and-mortar establishments, which find themselves in competition with online platforms that are endowed with inherent advantages and must also contend with rivalry from other physical retail outlets. In response, local retailers are compelled to adapt their strategies for product and service offerings. They are actively exploring innovative approaches to attract consumers in the digital shopping realm, bridging the divide between consumers and their storefronts by harnessing the potential of online interfaces [34].

DISCUSSION

Space for Sustainable Consumption Behavior: Local Commerce

Food processing and transportation processes entail significant energy consumption, primarily attributable to water utilization and the generation of waste. In developed nations, an increasing level of consumer consciousness regarding the environmental and societal repercussions embedded within the food supply chain has ushered in a proliferation of single-use plastic-free grocery establishments. While these novel retail entities represent a sustainable alternative, their environmental and societal merits, as well as their utilization potential, are inadequately communicated to consumers. Empirical evidence gleaned from surveys underscores the potential for stimulating resource-efficient behavior among consumers when they are apprised of the reduction in packaging waste and food waste resultant from patronizing these stores. Alternative retail concepts that amalgamate principles of organic food provisioning, ethical sourcing, and zero-packaging systems into conventional local supermarkets offer a promising avenue for the development of sustainable local commercial centers [35, 36].

An alternative approach involves harnessing the existing network of brick-and-mortar stores as logistical hubs, with particular emphasis on the ubiquitous presence of convenience stores in virtually every locality. Traditionally, convenience stores have primarily functioned as conventional supermarkets; however, the advent of novel delivery modalities such as quick commerce and early morning delivery opens up new vistas for this business model to realize its niche potential [37]. This can be achieved through diversifying the product repertoire to encompass fresh and small-quantity food items. Notably, South Korea's prominent convenience store franchise, CU, has undertaken a transformational initiative by outfitting convenience stores with dedicated refrigeration units for fresh meat and establishing meal kit stands, thereby optimizing their role as logistical hubs. Given the widespread ubiquity of convenience stores within urban landscapes, with outlets nestled in every

nook and cranny, this presents an opportunity to establish logistical hubs in close proximity to consumers [38].

Despite the corporate ownership of convenience store chains, franchisees are individual entrepreneurs, warranting consideration of national-level support mechanisms to bolster their operations and incentivize sustainable consumer behavior, capitalizing on the accessibility inherent to these retail outlets. In parallel, it is imperative to recognize that environmental concerns have assumed a dimension of critical importance akin to security considerations. As such, state actors, businesses, and non-governmental organizations are endowed with a pivotal role in shaping decision-making processes that influence individual behaviors aimed at mitigating environmental harm and ensuring the availability of sustainable options [39].

Space for Sustainable Consumption Behavior: Local Commerce: Personal Space

Individuals who exhibit a forward-looking orientation possess the cognitive capacity to envision themselves engaging in sustainable behaviors and project the implications of such actions onto their future selves. This forward-thinking mindset assumes a pivotal role in fostering increased adoption of sustainable behaviors within their daily lives, primarily by heightening their awareness of associated risks and fostering deeper engagement in sustainable practices [40].

These forward-looking individuals actively curate their personal spaces to accommodate sustainable consumption behaviors. They actively seek out stores that introduce alternative retail concepts to the conventional neighborhood supermarket, establishing them as their preferred shopping destinations. In this personalized realm, they diligently embrace sustainable consumption practices aimed at reducing their personal carbon footprint. An exemplar of this is the practice of 'home gardening.' Home gardening is a potent avenue for exercising sustainability within one's personal space, underpinned by dual rationales. Firstly, it promotes a wholesome lifestyle, yielding psychological and physical health benefits. Home gardening encompasses various facets, including vegetable cultivation, gardening, and potted plant maintenance, all of which confer the environmental benefit of air purification and cleansing within one's immediate environment [41]. Home gardening can also be regarded as a form of small-scale, self-sustaining urban agriculture, with households cultivating their own produce. By nurturing their own fruits and vegetables, individuals not only reduce their carbon footprint but also circumvent the pollution associated with various external services, including water wastage and energy consumption in transportation. Furthermore, it facilitates the reduction of food wastage, as individuals can cultivate and consume only what is needed within their personal space. The presence of a home garden ensures easy access to fresh produce on a daily basis, thereby enhancing food security, diversification, and environmental sustainability in the vicinity of one's residence [42, 43]. Notably, businesses have responded to this

trend by introducing home gardening kits, facilitating the integration of sustainability into individuals' daily lives.

Forward-thinking consumers, especially the younger demographic, wield considerable influence by effecting a positive ripple effect. They actively propagate sustainability within their personal spheres and leverage the reach of social networking services (SNS), an intimate yet communal platform, to inspire fellow consumers to voluntarily adopt sustainable practices. Younger consumers, in particular, are more inclined and capable of disseminating examples of green local store reviews and sustainable dietary practices within their generational cohort [44].

CONCLUSION

In the contemporary world, characterized by a fervent pursuit of speed and efficiency, the quick commerce sector thrives by leveraging the rapidity of consumer trends as a strategic advantage. However, the escalating adoption of quick commerce practices has inevitably engendered adverse environmental consequences. These repercussions encompass infrastructure development to secure warehouses, heightened vehicular traffic stemming from frequent transportation activities, and an upsurge in packaging waste generated during product deliveries, thereby contributing to air pollution. Concurrently, the local retail establishments in our immediate communities are grappling with the ramifications of surging demand for quick commerce, underscoring the need to redress the inequitable concentration of food security within specific socioeconomic strata and urban centers. The imperative now calls for a paradigm shift toward consumption patterns characterized by sustainability considerations. This transformation transcends the individual level, necessitating robust national-level support for existing local retailers in their endeavors to embrace alternative retail concepts founded on principles of organic food provisioning, ethical sourcing, and the adoption of zero-packaging systems. On an individual front, consumers can contribute to sustainability within their immediate surroundings through engagement in home gardening activities, which not only enhance the quality of their personal environment but also establish self-sustaining food systems.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

REFERENCES

- [1] S. Y. Alwan, Y. Hu, A. A. M. H. Al Asbahi, Y. K. Al Harazi, and A. K. Al Harazi, "Sustainable and resilient e-commerce under COVID-19 pandemic: a hybrid grey decision-making approach," *Environmental Science and Pollution Research*, Vol. 30(16), pp. 47328–47348, 2023. [\[CrossRef\]](#)
- [2] M. Arvidsson, N. Lovsjö, and M. Keuschnigg, "Urban scaling laws arise from within-city inequalities," *Nature Human Behaviour*, Vol. 7(3), pp. 365–374, 2023. [\[CrossRef\]](#)
- [3] T. Ben Hassen, and H. El Bilali, "Impacts of the Russia-Ukraine war on global food security: Towards more sustainable and resilient food systems?," *Foods*, Vol. 11(15), Article 2301, 2022. [\[CrossRef\]](#)
- [4] D. Brevers, C. Baeken, P. Maurage, G. Sescousse, C. Vögele, and J. Billieux "Brain mechanisms underlying prospective thinking of sustainable behaviours," *Nature Sustainability*, Vol. 4(5), pp. 433–439, 2021. [\[CrossRef\]](#)
- [5] L. Cabernard, S. Pfister, C. Oberschelp, and S. Hellweg, "Growing environmental footprint of plastics driven by coal combustion," *Nature Sustainability*, Vol. 5(2), pp. 139–148, 2021. [\[CrossRef\]](#)
- [6] T. Chang, J. Graff Zivin, T. Gross, and M. Neidell, "Particulate pollution and the productivity of pear packers," *American Economic Journal: Economic Policy*, Vol. 8(3), pp. 141–169, 2016. [\[CrossRef\]](#)
- [7] T. Y. Chang, J. Graff Zivin, T. Gross, and M. Neidell, "The effect of pollution on worker productivity: Evidence from call center workers in China," *American Economic Journal: Applied Economics*, Vol. 11(1), pp. 151–172, 2019. [\[CrossRef\]](#)
- [8] C. Y. Kim, and C. Park, "A case study on freshcode for the food online platform business: A focus on the lean start-up," *Journal of Information Technology Services*, Vol. 20(5), pp. 89–104, 2021.
- [9] J. Chu, H. Liu, and A. Salvo, "Air pollution as a determinant of food delivery and related plastic waste," *Nature Human Behaviour*, Vol. 5(2), pp. 212–220, 2021. [\[CrossRef\]](#)
- [10] D. H. Galhena, R. Freed, and K. M. Maredia, "Home gardens: a promising approach to enhance household food security and wellbeing," *Agriculture and Food Security*, Vol. 2(1), pp. 8, 2013. [\[CrossRef\]](#)
- [11] E. E. Garnett, and A. Balmford, "The vital role of organizations in protecting climate and nature," *Nature Human Behaviour*, Vol. 6(3), pp. 319–321, 2022. [\[CrossRef\]](#)
- [12] K. Hayakawa, H. Mukunoki, and S. Urata, "Can e-commerce mitigate the negative impact of COVID-19 on international trade?," *The Japanese Economic Review*, Vol. 74(2), pp. 215–232, 2023. [\[CrossRef\]](#)
- [13] J. He, H. Liu, and A. Salvo, "Severe air pollution and labor productivity: Evidence from industrial towns in China," *American Economic Journal: Applied Economics*, Vol. 11(1), pp. 173–201, 2019. [\[CrossRef\]](#)

- [14] H. P. Gund, and J. Daniel, "Q-commerce or E-commerce? A systematic state of the art on comparative last-mile logistics greenhouse gas emissions literature review," *International Journal of Industrial Engineering and Operations Management*, pp. 1–23, 2023. [\[CrossRef\]](#)
- [15] M. Schorung, "Quick commerce: will the disruption of the food retail industry happen? Investigating the quick commerce supply chain and the impacts of dark stores," [Postdoctoral Dissertation] Université Gustave Eiffel, 2023.
- [16] J. Allen, M. Piecyk, T. Cherrett, M. N. Juhari, F. N. Mcleod, M. Piotrowska, O. Bates, T. Bektas, K. Cheliotis, A. Friday, and S. Wise, "Understanding the transport and CO2 impacts of on-demand meal deliveries: A London case study," *Cities*, Vol. 108, Article 102973, 2021. [\[CrossRef\]](#)
- [17] Department for Transport, "Transport and Environment Statistics: Autumn 2021," UK, 2021.
- [18] M. Jaller and A. Pahwa, "Evaluating the environmental impacts of online shopping: A behavioral and transportation approach," *Transportation Research Part D: Transport and Environment*, Vol. 80, Article 102223, 2020. [\[CrossRef\]](#)
- [19] J. A. Cano, A. Londoño-Pineda, and C. Rodas, "Sustainable logistics for e-commerce: A literature review and bibliometric analysis," *Sustainability*, Vol. 14(19), Article 12247, 2022. [\[CrossRef\]](#)
- [20] R. Mangiaracina, A. Perego, A. Seghezzi, and A. Tumino, "Innovative solutions to increase last-mile delivery efficiency in B2C e-commerce: a literature review," *International Journal of Physical Distribution & Logistics Management*, Vol. 49(9), pp. 901–920, 2019. [\[CrossRef\]](#)
- [21] M. Kiba-Janiak, J. Marcinkowski, A. Jagoda, and A. Skowrońska, "Sustainable last mile delivery on e-commerce market in cities from the perspective of various stakeholders. Literature review," *Sustainable Cities and Society*, Vol. 71(21), Article 102984, 2021. [\[CrossRef\]](#)
- [22] Kawa, and J. Świątowiec-Szczepańska, "Logistics as a value in e-commerce and its influence on satisfaction in industries: a multilevel analysis," *Journal of Business & Industrial Marketing*, Vol. 36(13), pp. 220–235, 2021. [\[CrossRef\]](#)
- [23] X. Wang, K. F. Yuen, Y. Wong, and C.-C. Teo, "E-consumer adoption of innovative last-mile logistics services: A comparison of behavioural models," *Total Quality Management & Business Excellence*, Vol. 31(11-12), pp. 1381–1407, 2018. [\[CrossRef\]](#)
- [24] K. H. M. Mansur, Q. Zhu, et al., "AMOS-based analysis of factors influencing customer loyalty," *E3S Web of Conferences*, Vol. 251, 2021. [\[CrossRef\]](#)
- [25] J. T. Anderson, T. Prasertwit, J. Luo, and S. Cao, "Preliminary Study of Environmental Impact Related to E-commerce Activities in Thailand," *E3S Web of Conferences*, Vol. 259, 2021. [\[CrossRef\]](#)
- [26] S. Akıl, and M. C. Ungan, "E-commerce logistics service quality," *Journal of Electronic Commerce in Organizations*, Vol. 20(1), pp. 1–19, 2021. [\[CrossRef\]](#)
- [27] A. Oluyemi, and A. Ogbogu-Nzoiwu, "Green design or multiple re-useable product packaging as regards solid waste in selected areas in Awka Metropolis, Nigeria," *Environmental Research and Technology*, Vol. 6(3), pp. 266–2728, 2023. [\[CrossRef\]](#)
- [28] M. Shen, W. Huang, M. Chen, B. Song, G. Zeng, and Y. Zhang, "(Micro)plastic crisis: Un-ignorable contribution to global greenhouse gas emissions and climate change," *Journal of Cleaner Production*, Vol. 254, Article 120138, 2020. [\[CrossRef\]](#)
- [29] H. Duan, G. Song, S. Qu, X. Dong, and M. Xu, "Post-consumer packaging waste from express delivery in China," *Resources, Conservation and Recycling*, Vol. 144, pp. 137–143, 2019. [\[CrossRef\]](#)
- [30] W. Fan, M. Xu, X. Dong, and H. Wei, "Considerable environmental impact of the rapid development of China's express delivery industry," *Resources, Conservation and Recycling*, Vol. 126, pp. 174–176, 2017. [\[CrossRef\]](#)
- [31] W. C. Li, H. F. Tse, and L. Fok, "Plastic waste in the marine environment: A review of sources, occurrence and effects," *Science of The Total Environment*, Vol. 566-567, pp. 333–349, 2016. [\[CrossRef\]](#)
- [32] A. Maki, A. R. Carrico, K. T. Raimi, H. B. True-love, B. Araujo, and K. L. Yeung, "Meta-analysis of pro-environmental behaviour spillover," *Nature Sustainability*, Vol. 2(4), pp. 307–315, 2019. [\[CrossRef\]](#)
- [33] M. Samudio Lezcano, C. D. Harper, D. Nock, G. V. Lowry, and J. J. Michalek, "Online grocery delivery: Sustainable practice, or congestion generator and environmental burden?," *Transportation Research Part D: Transport and Environment*, Vol. 119, Article 103722, 2023. [\[CrossRef\]](#)
- [34] B. Morgan, "3 lasting changes to grocery shopping after covid-19," *Forbes*, <https://www.forbes.com/sites/blakemorgan/2020/12/14/3-lasting-changes-to-grocery-shopping-after-covid-19/?sh=6df4a88554e7> 2020.
- [35] G. Myovella, and M. Karacuka, "Digitalization and economic growth: A comparative analysis of Sub-Saharan Africa and OECD economies," *Telecommunications Policy*, Vol. 44(2), 2020. [\[CrossRef\]](#)
- [36] N. Duch-Brown, L. Grzybowski, A. Romahn, and F. Verboven, "The impact of online sales on consumers and firms. Evidence from consumer electronics," *International Journal of Industrial Organization*, Vol. 52, pp. 30–62, 2017. [\[CrossRef\]](#)
- [37] N. Gilliland, "Q-commerce: How is the rapid grocery market faring amid rising challenges?," *Econsultancy*, <https://econsultancy.com/q-commerce-grocery-challenges-2022/> 2022.
- [38] S. Park, and K. Lee, "Examining the impact of e-commerce growth on the spatial distribution of fashion and beauty stores in Seoul," *Sustainability*, Vol. 13(9), Article 5185, 2021. [\[CrossRef\]](#)
- [39] C. Payne, "Environmental impact of food equity," *Nature Human Behaviour*, Vol. 3(11), Article 1137, 2019. [\[CrossRef\]](#)

-
- [40] J. Scott, “The changing global geography of low-technology, labor-intensive industry: clothing, footwear, and furniture,” *World Development*, Vol. 34(9), pp. 1517–1536, 2006. [\[CrossRef\]](#)
- [41] S. Eng, T. Khun, S. Jower, and M. J. Murro, “Healthy lifestyle through home gardening: The art of sharing,” *American Journal of Lifestyle Medicine*, Vol. 13(4), pp. 347–350, 2019. [\[CrossRef\]](#)
- [42] S. Poonpolsuba, N. Jakrawatanab, M. Pattarapremcharoen, and W. Setthapun, “Carbon footprint reduction from Bangkok urban home vegetable garden,” *International Journal of Renewable Energy*, Vol. 12(2), pp. 75–86, 2017.
- [43] J. Vávra, P. Daněk, and P. Jehlička, “What is the contribution of food self-provisioning towards environmental sustainability? A case study of active gardeners,” *Journal of Cleaner Production*, Vol. 185, pp. 1015–1023, 2018. [\[CrossRef\]](#)
- [44] K. L. Webb, and C. J. Lambe, “Internal multi-channel conflict: An exploratory investigation and conceptual framework,” *Industrial Marketing Management*, Vol. 36(1), pp. 29–43, 2007. [\[CrossRef\]](#)



Review Article

Review on the use of artificial neural networks to determine the relationship between climate change and the occupancy rates of dams

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ARTICLE INFO

Article history

Received: 09 August 2023

Revised: 16 November 2023

Accepted: 25 November 2023

Key words:

Amount of water; Artificial neural network; Climate change; Global warming

ABSTRACT

Climate change has the potential to raise temperatures, alter precipitation patterns, and alter how water resources are distributed globally. The occupancy rates of drinking water supplies may change as a result of these changes. For instance, dwindling water supplies may result from rising temperatures and diminishing precipitation. As a result, the occupancy rates of the reservoirs may drop, making it harder to deliver drinking water. Climate change, however, might highlight regional variations and result in wetter conditions in some places. The occupancy rates in the reservoirs could rise in this scenario. Heavy rains, however, can also result in additional issues like infrastructure damage and floods. Climate change-friendly actions must be taken to manage water supplies in a sustainable manner. In the management of water resources, dams are crucial. It has been observed that when a reliable estimate of a dam's flow is provided, data-based models can produce valuable findings for a variety of hydrological applications. It is obvious that one of the most important problems is the difficulty in getting utility and drinking water as a result of climate change and other things. The purpose of this study is to compile the works that can be offered as a result of the literature review on the impact of climate change on surface water resources and dams, given the importance of this topic. As a result of this study, we can deduce a link between the occupancy levels of the reservoirs used to supply drinking water and climate change. Climate change has the capacity to increase temperatures, modify precipitation patterns, and shift the distribution of water supplies. The relationship between climate change and water supplies is better understood thanks to this study.

Cite this article as: Furkan Demirbaş, Emine Elmaslar Özbaş. Review on the use of artificial neural networks to determine the relationship between climate change and the occupancy rates of dams. Environ Res Tec 2024;7(1)140–147.

INTRODUCTION

As stated in the United Nations Framework Convention on Climate Change (FCCC), "change in climate as a result of human activities that directly or indirectly disrupt the composition of the global atmosphere, in addition to natural climate change observed over a comparable time period" is considered climate change [1].

With rising population and advancing industry, there have been noticeable increases in greenhouse gas emissions,

which have exacerbated global warming by enhancing the atmosphere's already-present greenhouse effect. The earth's climate has changed drastically and quickly as a result of these factors [2–4].

Climate change is a phenomenon that occurs on a long-term scale and over several millennia [5]. Environmental issues brought on by climate change include shifting precipitation patterns, polar ice caps melting, and rising sea levels [6]. Global warming is the primary cause of these changes [7]. Increased greenhouse gas emissions and ex-

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cessive energy absorption by the Earth's atmosphere are the causes of rising global temperatures. The energy balance between the sun and the Earth has been disturbed by rising greenhouse gas levels [8, 9].

Water resources are depleted as a result of climate change, and arid and semi-arid regions are expanding. As a result of excessive evaporation, desertification, salinization, and erosion are becoming more and more prevalent every day. Water stress is brought on by changes in the water cycle brought on by climate change and the unpredictability felt by nations with issues using their water resources [10]. 25.5% of Türkiye's land is at high risk of desertification, while 53.2% is at moderate risk, according to the "Combating Desertification Progress Report" issued in 2018. Climate change: It is predicted that the likelihood of desertification and the length and severity of droughts would both keep rising daily. According to the studies, Türkiye, which is situated in the Mediterranean Basin, is one of the riskier nations. The water resources of Türkiye, which is among the nations that are already experiencing water shortages in terms of usable water potential per capita, are anticipated to be negatively impacted by these changes in tandem with the changes in precipitation and temperatures [11, 12].

By the 2090s, climate change is expected to cause average temperatures in Southern Europe and the Mediterranean region, including Türkiye, to rise by up to 3.0-3.5°C and total precipitation to fall by 15–30% [13, 14]. These modifications are predicted to result in a large decrease in the water potential that is already there. As a result, it is possible to notice reductions in the existing water potentials of over 50% in the Mediterranean region and between 25% and 50% in the Aegean [15].

In order to gather enormous amounts of water or build a reservoir, dams are constructions that are often built on both sides of a river valley [16]. All nations rely on their rivers and lakes to provide water for irrigation or domestic and industrial water supplies. As a result, it is critical to always have enough water in water sources. Since precipitation and snowmelt determine surface water level, seasonality is a deciding element in surface water availability. In fact, there are times of the year when the river flow is high and may even be higher than the demand for water downstream. However, during dry spells, river flow can be extremely low, leading to water shortages. By holding excess water flow in a reservoir and releasing it when the flow is low or insufficient to fulfill full demand, the construction of dams enables the regulation of seasonality [17].

The structures used for water storage (reservoirs) are the most crucial part of water delivery systems where water needs are satisfied by surface water sources. Reservoirs are run according to operating curves that are designed to provide water storage at desired levels throughout the year. The fundamental goal of reservoir operation is to guarantee that the reservoir is filled up to the designated storage level in line with the operating curve during wet seasons, while still supplying the necessary flow, particularly during dry months. Operating curves were once calculated through

trial and error, but today they may be calculated using a variety of optimization approaches [18]. The majority of these techniques reliably calculate the volume of water storage needed to meet the need. Hydroclimatic data must be incorporated into the reservoir operation and decision-making system in order to improve water resource management. A water allocation decision support model that accepts input from climate-based forecasts can help with this integration. By essentially reducing the probability range of potential reservoir flows that can be determined from climatic information, the created decision support system enables better water distribution decisions [19].

An artificial neural network (ANN) is a mechanism for providing parallel information flow between organizations that was created using the same principles as the human brain [20].

The current issues are attempted to be resolved as cells are networked together. Through the relationships forged, information exchange is made possible by these connection values' capacity for learning. ANNs are computer systems that can carry out tasks like knowledge generation and discovery through learning with the aid of sample data. ANNs are designed for actions that cannot be foreseen [20]. ANN is employed in the areas of associating, learning, generalization, classification, reconciliation, and feature determination. It is described as a model that replicates the operation of the brain through a statistical analysis of sample data. By building networks and artificial cells to simulate all of the brain's behavior, scientists are creating a branch of study that acts independently of computer operations in their quest to understand the formula of the brain. As a result, ANN has become a brand-new branch of science. Nerves with several cells are arranged in layers to create ANNs. The first row of the network contains the input layers, while the last row has the output layers. Each layer is arranged in relation to the one beneath it and the one above it. The network topology, activation activities, accuracy rate, and training are all necessary for setting up an ANN.

It is clear that the difficulty in obtaining drinking and utility water due to climate change and other factors is a very critical issue. Given the significance of this topic, the goal of this study is to assemble the works that can be provided as a result of the literature review on the influence of climate change on dams and surface water resources. This study's goal is to support additional research in the future.

EXAMPLES FROM THE LITERATURE

A study on the detrimental impacts of a potential drought on Istanbul's water supplies was undertaken by Gerek et al. in 2007 [21]. A software program created by DSI (State Hydraulic Works) for reservoir operation was used to determine the amount of evaporation from the reservoirs in order to calculate the annual yields of these reservoirs in accordance with the results of the drought analysis. The study's scope included an examination of Istanbul's current water supply system.

In the study done in 2007 by Altunkaynak [22], it was utilized to estimate how the lake's water level changed over time as a result of Van Lake's rising water level and the flooding of the coastal districts. With the help of this study, it was determined that an artificial neural network could be used to estimate the link between precipitation and lake water level as well as the dynamic variations in the lake's water level [22].

Bates et al. [23] stated in a literature summary compiled on behalf of the IPCC that in the European continent, especially in England, the Netherlands, and Germany, adaptation and risk against the uncertainties that climate change will create on their water systems. This was based on studies looking at the effects of climate change on the supply reliability of dam reservoirs. They appear to carry out their calculations [23].

In the study done by Çalım [24], the level change of the dam reservoir was estimated using the 1796-day measurement data of Hatay, Antakya Yârseli Dam and its basin located in the Mediterranean Region. This method used artificial neural networks. The artificial neural network was modeled using the Boyesian organization method. In this instance, the Levenberg-Marquardt (LM) training procedure was used to update the weight and bias coefficients. When compared to data obtained using the conventional method, it has been observed that the estimation findings from the artificial neural network modeling study performed well [24]. The increased amount of reservoir evaporation brought to light by global warming and the rise in greenhouse gas concentration in the atmosphere by Benzaghta et al. [25]. For instance, it is said that 95% of Australia's precipitation has already evaporated. The study looked at both chemical and physical approaches to lowering reservoir evaporation. The results showed that while chemical approaches can impair water quality and reduce evaporation by 20% to 40%, physical methods can efficiently reduce evaporation without having an adverse effect on the environment [25].

Using flow-loss flow, precipitation, evaporation, withdrawn flow, level measurements measured by DSI (State Hydraulic Works) and entering Beyşehir Lake between 1962 and 1990, level values were estimated by artificial neural network in a study conducted by Yazar et al. [26], and the results obtained were compared with the estimation values. By removing the challenges associated with evaluating lake water level readings obtained using conventional techniques, it was hoped that the Beyşehir Lake study would help determine the lake's water level as quickly as possible [26].

Ustaoglu [27] noted that regional differences, particularly in precipitation amounts, come to the fore, with an increasing trend in the Black Sea Region and a decreasing trend predicted along the Aegean and Mediterranean coasts. His study examined the variability in precipitation amounts in Türkiye. Precipitation amounts are expected to shift, with the southern regions of Türkiye seeing a decrease and the northern sections of Türkiye experiencing an increase. The Aegean and Mediterranean coasts will

have the greatest (absolute) precipitation reductions. On the other side, greater precipitation is anticipated for the Eastern Black Sea region. There won't be much of a shift in precipitation in Central Anatolia.

The precipitation results from the future simulation, according to Önoğlu and Ünal [28], show that precipitation declines in almost all regions and in all seasons with the exception of autumn. Türkiye is situated in an area that is very vulnerable to climate change, according to Şen [29]. Future climate change predictions predict that temperatures will rise nationwide and that precipitation will fall, notably in the southern half of the country. It is clear that these changes will have a negative impact on the nation's water resources and reduce water potential, particularly in the southern portion of the basins. According to projections, until the middle of the present century, the reduction in water potential might reach 37% in the Mediterranean basins, 70% in the Konya basin, and 10% in the Euphrates and Tigris basins. The Tahtalı dam basin example was used in the Okkan [30] study to assess the effects of climate change on water resources. In the study, fourteen climate models and various climatic scenarios were used to predict changes in precipitation and temperature in the Tahtalı dam basin. By scaling these changes down to the station scale, local climate variations were discovered. The sensitivity of dam currents to potential changes was also investigated, along with sensitivity analyses to changes in temperature and precipitation. The results indicate that temperatures may rise by 1.5 °C to 2.1 °C, precipitation may drop by 3% to 13%, and flows may decrease by 9% to 22%. The volume of drinking water in this situation is predicted to drop by 11% to 35%, and water supply shortages may develop in the area.

Adeloye et al. [31] assessed how revised conservation-combined reservoir rule curves might affect Pong Reservoir's present and future performance under the influence of climate change in India. The HYSIM precipitation-runoff model's simulations of historical and climate change flow series serve as the foundation for the analyses. Delta changes in temperature (0 °C to +2 °C) and precipitation (10% to +10%) were used due to climatic concerns. A pair of consecutive peaks algorithm and a genetic algorithm optimizer are used to create rule curves for reservoir simulation together with simulated flow situations. Sustainability, dependability, recovery, and the greatest amount of shortages are used to summarize reservoir performance. According to the findings, the prior greatest scarcity has fallen from 61% to 20% below the 25% level that many water consumers can tolerate thanks to conservation efforts. While increased precipitation and more influx were anticipated, climate change fears in precipitation revealed the opposite outcome. Maximum water scarcity was worse than 66% without protection from reduced current; it was improved to 26% with this protection. An important outcome of this study has been the strengthening of operational procedures connected to hedging and the capacity to successfully eradicate the impacts of water scarcity brought on by climate change [31].

Two separate neural network models were employed in the study done in 2016 (Doğan et al.) [32] to estimate Lake Van's daily water level. Feedforward neural networks (FFNNs) and radial basis function neural networks (RBFNNs) are examples of these neural networks. The FFNN algorithm model beat the RBFNN algorithm model when the estimation results were compared using the mean square error (MES) and R^2 (determination) coefficients. A threat won't be posed by an increase in water in the rapidly growing and densely populated areas around Van Lake's coast because it has been determined from the estimation results of this study that the water level of Van Lake will fall in the future [32].

In their 2016 study, Soundharajan et al. [33] looked at the Pong Reservoir in India, which is situated on the Beas River. To explain the uncertainties brought on by climate change in the storage need and reservoir performance, they employed the Monte-Carlo simulation approach. The software simulates calibrated precipitation-temperature and precipitation-runoff scenarios. Due to the future's drier climate, the reservoir capacity in the results revealed a significant coefficient variability of 0.3 [33].

Yang et al. [34] seek to develop adaptive multi-purpose business rules to lessen variability. An adaptive multi-purpose operating model is suggested and built together with the combination of operating rule curves and reservoir operating function. These ideal operating guidelines are created by contrasting and discussing the NSGA-II approach and dynamic programming. The most effective operating rules were chosen using the projection tracking approach. The findings demonstrated that using NSGA-II to develop reservoir operating rules can boost dependability, water resource efficiency, and hydroelectric energy production. In particular, these water resource-focused rules can significantly increase reservoir annual water resource efficiency by 18.7%. This demonstrated the effectiveness of the suggested paradigm for reservoir operation in terms of climate change [34].

In the Zhao et al. [35] study, the Distributed Hydrology Soil Plant Model (DHTBM) included a multi-purpose reservoir module with established complex operation rules. This module has been modified to accommodate conditional operating rules created to improve the consistency of water delivery and lower the risk of floods. Two reservoirs on the Brazos River in Texas (Whitney and Aquilla) were used to assess the effectiveness of this integrated model. The model has been tested and calibrated using data on reservoir storage and observed input and output currents. Daily, weekly, and monthly data for both reservoirs are a summary of inaccurate figures (reservoir capacity, volume of water discharged, hydraulic power). The Nash-Sutcliffe Coefficient was 0.75 and the coefficient of determination (R^2) was 0.85 when using the Whitney Reservoir's weekly reservoir storage capabilities. With the addition of new reservoir components, DMTBM has demonstrated that it is a platform that supports equitably managing water resources in the face of growing anthropogenic activity and ongoing environmental change [35].

The impact of weather information on variations in the water level in the Yalova Gökçe Dam and the impact of climate change on lake water level were both investigated in the study by Sönmez et al. [36]. Daily rainfall in the dam basin, daily evaporation, lake water level elevations, flow rates into the dam lake, and flow rates out of the dam were all employed for this purpose. The monthly and yearly fluctuations of these values were then looked at. With regard to population and water consumption per person in 2023, it has been stated that the changes in the dam's water level will not be sufficient due to the effects of global warming. [36].

The objective of the study carried out by Abu Salam in 2018 [37] was to determine the water level of the Dibis Dam, which is situated northwest of Kirkuk. The artificial neural network's input data set consisted of 10-year data. These information includes measurements of the initial water level, precipitation, and the flow values going into and out of the dam. The remaining 20% was utilized as test data, and the remaining 80% as training data. All models are fed via the forward back propagation learning technique in artificial neural network modeling. Four alternative analysis models were developed for the analyses. These analytical models include rainy/non-precipitated, initial water level with/without. The beginning water level was shown to be a crucial piece of information in this investigation [37].

The water budgets of the basins that provide Istanbul with drinking water were calculated using hydrological process models in the Cüceloğlu [12] study. Additionally, the effects of climate change on water supplies were examined using the results from global climate models. Analyses of Istanbul's water resources system's current state and potential impacts of climate change have been done. Water budget simulations have shown the future situation of Istanbul's water supply system. Approaches to dynamic modeling have proved successful in evaluating water resource management and watershed systems. In order to assess the existing state of Istanbul's water resources system and investigate the implications of climate change, a modeling infrastructure has been created.

The goal of the study by Damla et al. [38] was to use an artificial neural network to predict the water level of the Yalova Gökçe Dam. The Sellimandra stream flow rate, basin precipitation and evaporation values, dam water discharges, leachate volume, and dam water level statistics have all been used to try and estimate the water level in 2019. The findings collected indicated that the artificial neural network model's predictions were rather accurate in describing the actual water level. The estimated water level and the measured water level converged, with the determination rate determined at 94.14%. In general, it was found that the estimates were higher than the measured values, but in July and September, it was found that the estimates were lower than the measured values. The findings of this study indicate that using artificial neural network methods to estimate water levels can be advantageous for dam operations.

The Sono, Manuel Alves da Natividade, and Palma basins in the Cerrado region of Brazil were the subject of an investigation by Rodrigues et al. [39] on the hydrological impacts of climate change under several emission scenarios for the 21st century. In order to achieve this, the HadGEM2-ES and MIROC5 global climate models, along with the RCP4.5 and RCP8.5 scenarios, were used to run the SWAT hydrological model throughout three time periods (2011–2040, 2041–2070, and 2071–2099). Droughts were defined using the Standardized Precipitation Index (SPI) and the Standardized Stream Flow Index (SSFI). Overall, the findings indicate that future periods are likely to see an increase in the length, severity, and frequency of meteorological and hydrological droughts. However, it is anticipated that hydrological droughts will be more severe than meteorological droughts. Reduced stream flows are seen in both scenarios and over all future time periods, especially during dry spells. This could have a negative impact on the Cerrado biome's ecological processes, diminish aquifer recharge, and increase the risk of producing electricity in northern Brazil. The Sono, Manuel Alves da Natividade, and Palma Cerrado basins' hydrological behavior in the current climate was successfully reconstructed by the SWAT model. These findings demonstrate that it is possible to investigate how stream flow in the basins of the Cerrado Region is affected by climate change. Reductions in the annual water budget (P-ET) have been predicted by the Eta/HadGEM2-ES and Eta/MIROC5 climate models for the whole 21st century. The SWAT model expected declines in monthly stream flow throughout the year under these conditions. The dry season (June to August) had the largest monthly stream flow fluctuations, with decline rates reaching 90.1%. The RCP8.5 scenario (Eta/HadGEM2-ES) predicts the greatest changes in mean annual flow at the end of the twenty-first century, with 81.9% (412.2 mm), 75.4% (411.6 mm), and 81.9% (411.6 mm) in MRB, PRB, and SRB, respectively. A reduction of 74.7% (443.3 mm) is visible. A rise in the length, severity, and frequency of climatic and hydrological droughts is also predicted for the foreseeable future. However, it is anticipated that hydrological droughts will be more severe than meteorological droughts. Generally speaking, the outcomes from the various climatic scenarios used show large variations. The findings indicate that the availability of water in Brazil's Cerrado region may be significantly impacted by climate change. Therefore, it is important to draw attention to the hazards for decreased aquifer recharge, northern Brazil's electrical power production, and the Cerrado Region's environment.

According to the most recent IPCC 6th Report [40], droughts would negatively affect Türkiye in the coming years, notably in Türkiye, according to model results obtained in accordance with SSP scenarios. There is a trend toward rising temperatures and falling precipitation, as shown by the scenarios and models customized for Türkiye in the report Climate Projections for Türkiye issued by the General Directorate of Meteorology [41]. Ayva et al. [42] attempted to analyze the existing impact of climate change and its potential future implications in the Kirazdere basin, a sub-basin of the Yuvacık Dam, a significant water resource in the Kocaeli province. The Mann

Kendall trend analysis results show that there has been a significant increase in temperatures, particularly after the 2000s, and that temperatures have been growing throughout the analyzed time. While there was no discernible trend in the precipitation, the flow was seen to be diminishing. Additionally, the analysis of the Standardized Precipitation Index (SPI) revealed that there were times of drought. Drone photographs showed that there had been drops in water level in the dam lake as a result of the drought. Some scenarios forecast an increasing trend in temperature and a declining trend in precipitation based on climate models and scenarios. The results of the drought analysis indicate that the basin will experience both short-term and long-term droughts in the future.

In their study from 2023, Salmona et al. [43] assessed how land development and climate change affected 81 watersheds in Brazil's Cerrado ecosystem. A future deforestation and climate scenario up to 2050 was projected, and their impact on land and water was estimated, based on a thorough examination of field and secondary data collected between 1985 and 2018. It has been noted that river flows are more strongly impacted by the direct effects of large-scale deforestation on the production of irrigable agricultural crops than climate changes. According to estimates, the flow reduced because of deforestation and climate change by 8.7% and 6.7%, respectively. Due to changes in land use and land cover, the majority of the observed changes (56.7%) took place in the last ten years. The Cerrado basins have had a total water reduction of 19,718 m³/s as a result of changes in climate, land use, and land cover. Assuming current deforestation rates, the total amount of water lost by 2050 will be 23,653 m³/s, which translates to a 33.9% reduction in river flows in the study area. This will severely alter numerous rivers' flows and have a negative impact on agriculture, the production of electricity, biodiversity, and water supplies, especially during the region's dry seasons. The findings demonstrate how changes in land use and the climate have a direct impact on the amount of surface water in Brazil's Cerrado habitat, which tends to get worse over time. Future projections reveal that the growth of agricultural areas tends to limit water flow in more than 90% of the basins in the Cerrado biome. This could result in repeated levels of water shortages during dry spells in the research area, it was highlighted in the study. The availability of water in the Cerrado biome is impacted by changes in land use and the climate, it was concluded.

CONCLUSIONS

We can infer a connection between climate change and the occupancy levels of the reservoirs used to supply drinking water. Climate change has the potential to raise temperatures, alter precipitation patterns, and alter how water resources are distributed globally.

The occupancy rates of drinking water supplies may change as a result of these changes. For instance, dwindling water supplies may result from rising temperatures and diminishing precipitation. As a result, the occupancy rates of the reservoirs may drop, making it harder to deliver drinking water.

However, there may be regional variations in the correlation between climate change and drinking water reservoir occupancy rates. Extreme weather conditions including increasing rainfall and flooding could occur in some locations. In this scenario, reservoir occupancy rates would climb, but other difficulties, such as excessive flooding and infrastructure issues, might also appear.

The occupancy rates of drinking water reservoirs and climate change are intricately related, in our opinion. Understanding how climate change affects water resources will help us modify our water management plans. Future drinking water supplies, resource protection, and efficient water use should all be goals of sustainable water resource management.

Precipitation patterns may alter as a result of climate change. Less precipitation may fall in some areas, while heavy rain and flooding may occur in other areas. Future precipitation patterns will be impacted by climate change, according to climate models. The occupancy rates of reservoirs holding potable water may be impacted by this.

Although drinking-use water consumption accounts for a small portion of global and national consumption, it is claimed that surface water resources provide the majority of the drinking-use water required in major cities. Due to shifting climatic conditions, rapid population increase, and changes in land use, it is challenging to obtain drinking-use water from surface water resources. As a result, it is imperative to manage and evaluate the effects of water resources using dynamic approaches that take both human activities and the hydroclimate's effects into consideration. To ensure the sustainable use of water resources, it is crucial to develop policies that are favorable to climate change. To do this, strategies for reducing water usage should be developed and put into practice, such as changing patterns of water consumption, calculating water footprint reduction, disseminating appropriate water utilization technology, and regulating water use in the industrial sector.

Due to their capacity to contain water and regulate flow, dams are valued assets for flood avoidance as well as for water supply and hydroelectric power. They play a significant role in the management of water resources. This is a crucial function because of the recent rise in extreme occurrences brought on by climate change, and future decades will depend heavily on our capacity to reduce flood damage. For water management or early warning systems, having a reliable estimate of a dam's flow might be advantageous. Data-based models have shown to be an effective tool for a variety of hydrological applications when historical data is available.

Acknowledgements

This study was produced from the doctoral thesis of the first author titled "Determination of the Effect of Climate Change on the Occupancy Rates of Dams Used for Drinking Water Supply by Artificial Neural Network Modeling" (IUC Institute of Graduate Studies - Department of Environmental Engineering).

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

REFERENCES

- [1] UN/FCCC, "Ministerial Declaration, United Nations Framework Convention on Climate Change," Conference of the Parties, Second Session. Geneva, 1996.
- [2] M. Parry, N. Arnell, G. Fisher, A. Iglesias, S. Kovats, M. Livermore, C. Rosenzweig, A. Iglesias, and G. Fischer, "Millions at risk: defining critical climate change threats and targets," *Global Environmental Change*, Vol. 11, pp. 181–183, 2001. [\[CrossRef\]](#)
- [3] J. G. Canadell, C. Quéré, M. R. Raupach, C. B. Field, E. T. Buitenhuis, P. Ciais, T. J. Conway, N. P. Gillett, R. A. Houghton, and G. Marland, "Contributions to accelerating atmospheric CO₂ growth from economic activity, carbon intensity, and efficiency of natural sinks," *Proceedings of the National Academy of Sciences*, Vol. 104(47), pp. 18866–18870, 2007. [\[CrossRef\]](#)
- [4] J.B. Smith, S.H. Schneider, M. Oppenheimer, G.W. Yohe, W. Haref, M. D. Mastrandrea, A. Patwardhan, I. Burton, J. Corfee-Morlot, C. H. D. Magadza, H.-M. Fussel, A. B. Pittock, A. Rahman, A. Suarez, and J.-P. van Ypersele, "Assessing dangerous climate change through an update of the Intergovernmental Panel on Climate Change (IPCC) 'reasons for concern,'" *Proceedings of the National Academy of Sciences*, Vol. 106, pp. 4133–4137, 2009. [\[CrossRef\]](#)
- [5] M. Ghiasi, N. Ghadimi, and E. Ahmadiania, "An analytical methodology for reliability assessment and failure analysis in distributed power system," *SN Applied Science*, Vol. 1(1), Article 44, 2019. [\[CrossRef\]](#)
- [6] Q. Huangpeng, W. Huang, and F. Gholinia, "Forecast of the hydropower generation under influence of climate change based on RCPs and developed crow search optimization algorithm," *Energy Reports*, Vol. 7, pp. 385–397, 2021. [\[CrossRef\]](#)
- [7] M. Mir, M. Shafieezadeh, M. A. Heidari, and N. Ghadimi, "Application of hybrid forecast engine based intelligent algorithm and feature selection for wind signal prediction," *Evolution System*, Vol. 11(4), pp. 559–573, 2020. [\[CrossRef\]](#)

- [8] X. Ren, Y. Zhao, D. Hao, Y. Sun, S. Chen, and F. Gholinia, "Predicting optimal hydropower generation with help optimal management of water resources by developed wildebeest herd optimization (DWHO)," *Energy Reports*, Vol.7, pp. 968–980, 2021. [CrossRef]
- [9] L.-N. Guo, C. She, D.-B. Kong, S.-L. Yan, Y.-P. Xu, M. Khayatnezhad and F. Gholinia, "Prediction of the effects of climate change on hydroelectric generation, electricity demand, and emissions of greenhouse gases under climatic scenarios and optimized ANN model," *Energy Reports*, Vol. 7, pp. 5431–5445, 2021. [CrossRef]
- [10] B. Ustaoglu, "Yucade iklim degisikligi ve etkileri: Su kaynaklari, tarim ve gida guvenligi," *ARGE Dergisi*, Vol. 31, 2021.
- [11] I. Dabanli, A. K. Mishra, and Z. Sen, "Long-term spatio-temporal drought variability in Turkey," *Journal of Hydrology*, Vol. 552, pp. 779–792, 2017. [CrossRef]
- [12] G. Cüceloğlu, "iklim degisikliginin Istanbul'un yuzeysel su kaynaklarina etkisi ve kuraklik direnci bütünüleşik su yönetimi," *Istanbul Teknik Üniversitesi, Doktora Tezi*, 501122710, 2019.
- [13] J. T. Houghton, Y. Ding, and D. J. Griggs, "Climate change 2001: the scientific basis. Contribution of working group I to the third assessment report of the intergovernmental panel on climate change," Cambridge University Press, 2001.
- [14] J. H. Christensen, B. Hewitson, and A. Busuioc, "Regional climate projections. In Solomon S, Qin D, Manning M, D. Qin, M. Marquis, K. Averyt, M. M. B. Tignor, H. LeRoy Miller Jr, and Z. Chen, (Eds.), *Climate change 2007: the physical science basis. Contribution of working group I to the fourth assessment report of the Intergovernmental Panel On Climate Change*," Cambridge University Press, 2007.
- [15] B. Lehner, T. Henrichs, P. Döll, and J. Alcamo, "EuroWasser – Model-based assessment of European water resources and hydrology in the face of global change," *Kassel World Water Series*, Vol. 5, pp. 124. Center for Environmental Systems Research, University of Kassel, Germany, 2001.
- [16] Devlet Su İşleri, "DSİ Genel Müdürlüğü - Teknik Sözlükler," 2014. <http://dsi.gov.tr/dsi-sozlukler>.
- [17] M. Davis, and D. Cornwell, "Introduction to Environmental Engineering (3rd ed.)," McGraw-Hill, pp. 22–36, 1998.
- [18] C. Brown, "Managing climate risk in water supply systems, Vol. 12," IWA Publishing, 2013. [CrossRef]
- [19] G. Cüceloğlu, "İklim degisikliginin istanbul'un yuzeysel su kaynaklarina etkisi ve kuraklik direnci bütünüleşik su yönetimi," *Doktora Tezi*, İstanbul Teknik Üniversitesi, Fen Bilimleri Enstitüsü, Çevre Mühendisliği Anabilim Dalı, Çevre Bilimleri ve Mühendisliği Programı, 2019.
- [20] T. Partal, "Türkiye yağış miktarlarının yapay sinir ağları ve dalgacık dönüşümü yöntemleri ile tahmini," *Istanbul Teknik Üniversitesi, Fen Bilimleri Enstitüsü*, İstanbul, 2007.
- [21] C. Gerek, M. Alp, A. Züran, V. Şahin, and İ. Kılınç, "Present conditions, future potentials, drought analysis and management of reservoirs around İstanbul," *International Congress River Basin Management*, Antalya, Turkey, March, 22–24, 2007.
- [22] Altunkaynak, "Forecasting surface water level fluctuations of Lake Van By artificial neural network," *Water Resour Manage*, Vol. 21, pp. 399–408, 2007. [CrossRef]
- [23] C. Bates, Z. W. Kundzewicz, S. Wu, and J. P. Palutikof, "Climate change and water," *Technical Paper of the Intergovernmental Panel on Climate Change*, pp. 210, 2008.
- [24] M. M. Çalım, "Yapay sinir ağları yöntemi ile baraj hazne kotu tahmini," *Yüksek Lisans Tezi*, Mustafa Kemal Üniversitesi, Fen Bilimleri Enstitüsü, Hatay, 2008.
- [25] M. A. Benzaghta, and T. A. Mohamad, "Evaporation from reservoir and reduction methods: An overview and assessment study," *International Engineering Convention*, Damascus, Syria, and Medina, Kingdom of Saudi Arabia, 2009.
- [26] A. Yazar, and M. Onüçyıldız, "Yapay sinir ağları ile beyşehir gölü su seviyesi degisimlerinin belirlenmesi," *Selçuk Üniversitesi Mühendislik Mimarlık Fakültesi Dergisi*, Vol. 24, pp. 21–30, 2009.
- [27] B. Ustaoglu, "Türkiye'de A2 emisyon senaryosuna göre ortalama yağış tutarlarının olası degisimi, (2010-2099)," *Fiziki Coğrafya Araştırmaları Sistematik ve Bölgesel. Prof. Dr. M.Y. Hoşgören'e Armağan Kitabı*, Türk Coğrafya Kurumu Yayınları, Vol. 6, pp. 473–484, 2011.
- [28] B. Önal, and Y. S. Ünal, "Assessment of Climate Change Simulations over Climate Zones of Turkey," *Regional Environ Change*. Springer-Verlag, 2012.
- [29] Ö. L. Şen, "Türkiye'de iklim degisikliginin bütünsel resmi," Öztopal, A., Yerli, B., Şen, Z. (Eds.), in: *Türkiye'de İklim Degisikligi Kongresi Proceeding Book*, Su Vakfı Yayınları, 2013.
- [30] U. Okkan, "İklim degisikliginin Akarsu Akışları Üzerindeki Etkilerinin Değerlendirilmesi," *Dokuz Eylül Üniversitesi Fen Bilimleri Enstitüsü Doktora Tezi İnşaat Mühendisliği Bölümü, Hidrolik – Hidroloji ve Su Kaynakları Anabilim Dalı*, 2013.
- [31] J. Adeloye, B. S. Soundharajan, C. S. P. Ojha, and R. Remesan, "Effect of hedging-integrated rule curves on the performance of the Pong Reservoir (India) during scenario-neutral climate change perturbations," *Water Resources Management*, Vol. 30, pp. 445–470, 2016. [CrossRef]
- [32] Doğan, U. Kocamaz, M. Utkucu, and E. Yıldırım, "Modelling daily water level fluctuations of Lake Van (Eastern Turkey) using artificial neural networks," *Fundamental and Applied Limnology*, Vol. 187, pp. 177–189, 2016. [CrossRef]
- [33] S. Soundharajan, A. J. Adeloye, and R. Remesan, "Evaluating the variability in surface water reservoir planning characteristics during climate change impacts assessment," *Journal of Hydrology*, Vol. 538, pp. 625–639, 2016. [CrossRef]

- [34] G. Yang, S. Guo, L. Li, X. Hong, and L. Wang, "Multi-objective operating rules for Danjiangkou Reservoir under climate change," *Water Resources Management*, Vol. 30, pp. 1183–1202, 2016. [CrossRef]
- [35] G. Zhao, H. Gao, B. S. Naz, S. C. Kao, and N. Voisin, "Integrating a reservoir regulation scheme into a spatially distributed hydrological model," *Advances in Water Resources*, Vol. 98, pp. 16–31, 2016. [CrossRef]
- [36] O. Sönmez, F. Demir, and D. Doğan, "Impact of climate change on Yalova Gokce Dam Water level," Published in 5th International Symposium on Innovative Technologies in Engineering and Science, ISITES2017 Baku – Azerbaijan, 29-30 September, 2017.
- [37] Z. K. A. Abu Salam, "Yapay sinir ağları ile dibis barajının seviye tahmini," Master Thesis, Süleyman Demirel Üniversitesi, Fen Bilimleri Enstitüsü, İnşaat Mühendisliği Ana Bilim Dalı, 2018.
- [38] Y. Damla, T. Temiz, and E. Keskin, "Estimation of water level by using artificial neural network: Example of Yalova Gökçe Dam," *Kırklareli University Journal of Engineering and Science*, Vol. 6, pp. 132–149, 2020. [CrossRef]
- [39] J. A. M. Rodrigues, M. R. Viola, L. A. Alvarenga, C. R. de Mello, S. C. Chou, V. A. de Oliveira, V. Uddameri, and M. A. V. Morais, "Climate change impacts under representative concentration pathway scenarios on streamflow and droughts of basins in the Brazilian Cerrado biome," *International Journal of Climatology*, Vol. 40, pp. 2511–2526, 2020. [CrossRef]
- [40] IPCC, 2021. <https://www.ipcc.ch/report/ar6/wg3/> Accessed on 01 Aug 01, 2022.
- [41] MGM, "Meteoroloji Genel Müdürlüğü, Türkiye için iklim projeksiyonları," <https://www.mgm.gov.tr/iklim/iklim-degisikligi.aspx?s=projeksiyonlar> Accessed on Aug 02, 2022).
- [42] C. Ayva, A. Atalay Dutucu, and B. Ustaoglu, "Climate Change Impact on Water Resources and Adaptation Strategies: The Case of Kirazdere Basin," *F.Ü. Sosyal Bilimler Dergisi*, Vol. 33(1), pp. 47–64, 2023. [CrossRef]
- [43] Y. B. Salmona, E. A. T. Matricardi, D. L. Skole, J. F. A. S. O. de A. C. Filho, M. A. Pedlowski, J. M. Sampaio, L. C. R. Castrillón, R. Albuquerque Brandão, A. Leme da Silva, and S. Aires de Souza, "A Wor-rying future for river flows in the Brazilian cerrado provoked by land use and climate changes," *Sustainability*, Vol. 15(5), Article 4251, 2023. [CrossRef]