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Research Article

Determination of tree type selection in park and garden construction by the value engineering method: Sinanoba Beach Park Example

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ABSTRACT

City parks are of great importance to people living in cities, and the presence of trees in the parks increases the value of the parks. There are many types of trees that can be planted in parks. However, it is not possible for every tree to adapt to every natural environment. In addition, the initial investment costs of the trees, the characteristics that may affect the life cycle costs, and the expectations of managers and park users from the trees also affect this choice. All these criteria should be evaluated together, and the ideal selection should be made. Value Engineering is a method that can be applied to make the most appropriate choice by taking into account the wishes of all stakeholders. Value engineering (DM) can be defined as an organized effort to analyze product features, functions and material selections; is designed to solve problems and/or reduce costs while maintaining or improving performance and quality requirements; and performs essential functions at the required quality, reliability, and life-cycle cost. In this study firstly a value engineering team was formed. The value engineering team decided that the trees should be coniferous with the prerequisite that they can remain green without shedding their summer-winter leaves and determined which criteria the coniferous trees required to be located in the park should meet. The team members conducted value engineering after determining which trees met these criteria and were subsequently purchased. In this study, since an existing project and a new project are not compared, it does not include a result on how much the cost gain is. As a result, the team determined the most appropriate optimum cost solution with the value engineering method to meet all the criteria among the determined alternative tree species.

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INTRODUCTION

Cities are settlements with an administrative organizational unit that contains a certain population where people live together and have the weight of industry and service sector in economic life [1]. The main purpose considered when establishing cities is to meet the basic vital needs of the people living in the city, and therefore, to create vital areas and tools that meet those needs [2]. A busy pace of work in cities often leads to life happening between home and work and in closed environments. Many problems, such as heavy traffic, poor air quality, trying to cope with many problems throughout the day, and stress, also affect the quality of life in cities. With the intensification of urbanization over time, it has become very important to create sports, entertainment, and recreation areas in cities for the psycho-

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logical rest and sociocultural development of people under the pressure of city life [3]. In such cases, people need to integrate with nature by moving away from densely structured environments and vehicle traffic. However, it may not always be possible to leave the city and access natural environments. For this reason, it is very important to build natural environments in cities, at distances that people can reach in a short time, in order to sustain life normally. City administrators build parks and gardens of different sizes in various parts of a city to meet the needs of people.

Green spaces are very important not only for the needs of living things but also for the livability of the world and the sustainability of natural life [4, 5]. Green areas reduce carbon emissions and provide benefits for the protection of the ozone layer [6–8]. Gardens contribute to green mitigation and energy transition and adaptive reuse of gardens can ecologically optimize user comfort and health in terms of microclimate and spatial quality [9].

Tourism is an important service sector for countries. Similar to other developing countries, national parks are not marketed much in Türkiye, but groves and national parks play an active role in foreign tourism [10]. If sufficient attention and care are given, parks and national parks will benefit domestic and foreign tourism. Central Park, located in the United States, which first comes to mind in regard to parks worldwide, has approximately 40 million visitors annually [11]. It is not possible to achieve this goal if parks such as Central Park are targeted. This can only be possible if the parks are designed to meet their unique needs.

There are many studies on city parks, trees in parks, and the benefits of these trees for the ecological environment [12–17]. Green spaces have positive effects on human well-being, climate, biodiversity, and air quality. These impacts enable cities to become more ideal and sustainable places to live and work [18]. In recent years, the importance of greening cities in adapting to urban climate change has been increasing. Climate change will lead to extreme temperatures and droughts, followed by extreme rainfall and flooding. This will place high demands on the urban environment [19]. Green trees and plants can prevent atmospheric CO_2 concentration on both a global and local scale. Trees and plants in a city can provide a significant cooling effect during heat waves. Considering the ecosystem services provided by green infrastructure to combat climate change, the quantity and health of trees that are part of green infrastructure is quite important as they provide fresh and clean air [20]. Covering the surfaces in cities with materials with high sealing rates prevents the natural flow of water, the infiltration of water into the soil and the growth of plants. In summary, this situation leads to an increase in surface flow rates [21]. Green spaces help keep these flows. Green cities, green roofs, facades, tree-lined streets, parks and forests compensate for heat through evaporative cooling. Therefore, greening and bluing the city is a complementary counter-strategy for cities under climate change, which consistently provides co-benefit to ecosystem services [22].

In a study by Stephen F., a total of 3,335 trees containing 79 species on the Austin State University (Nacogdoches, Texas, USA) campus and 1,572 trees containing 44 species in Nacogdoches city parks were investigated, and the health and regeneration values and differences between the two groups were statistically compared [23]. Kazemi et al. [24] proposed a low-input landscape design concept based on the efficient use of inputs, natural resources, and labor. Low-input landscape design is an approach that can accommodate many sustainable landscape design techniques and methods, including xeriscaping and water-sensitive urban design, which help to use resources effectively. Value engineering was used as the method for landscape design, and a cost reduction of 62.7% was achieved over the 20-year life cycle of a park. In another study, Kazemi et al. [25] measured people's preferences and perceptions about approaches to low-input design of traditional parks through three-dimensional designs of parks and interview-based questionnaires. In their study, Tochaiwat et al. [26] aimed to determine the eco-efficiency of trees on outdoor thermal comfort by examining the change in the ratio of the physiologically equivalent temperature in cities to the cost of trees planted in cities. In the study prepared by Guo and Mell [27], a number of thematic features that shape the planning and design of quality urban parks in China were identified through interviews with technical professionals consulting local governments on urban planning and landscape projects throughout China.

There are various studies on how to construct city parks from different perspectives. In their study, Yazıcı and Kiper [28] aimed to determine the spatial preferences of the urban landscape with a method developed based on visual perception specific to Topkapı city park. In his master's thesis, Demir [29] proposed the use of smart parking applications in Maltepe Fill Area Orhangazi City Park and examined the effects of the use of smart urban furniture in public spaces where smart urbanization is aimed at change and development in cities in Türkiye and İstanbul. Yücel and Yıldızcı [30], on the other hand, conducted a study on the establishment of quality criteria for urban parks.

The use of materials and methods that can meet the needs of the public, while creating parks enables parks to be more efficient [31]. One of the important issues to be determined here is what is needed. The term "need" refers to the product's expectations and the requirements that must be met. However, these expectations and criteria may have different meanings for the users or technical staff who produce that product. It must satisfy the needs of the users, technical staff members expect that all safety regulations and laws will be followed, architects desire an aesthetically pleasing design, and manufacturers hope to turn a profit on their creation. Then, whose criteria and expectations will be taken as the basis? What needs to be done here is to meet the expectations of all parties at an optimum level when producing any product. In addition, there are many alternative materials/methods that can meet all the criteria of stakeholders in solving these problems. Which of these is the right one to apply?

In this paper, a study was carried out to determine the tree species that should be planted in a park to be built in the city in a way that meets the criteria determined by the value engineering team through value engineering, which is a value-based method. In the study, a proportional amount of savings related to cost and other gains cannot be given, since an existing project and a proposed project are not compared. A choice of trees is needed for a new park. It was desired that the trees should be green in summer and winter, and for this reason, four types of coniferous tree species were determined as the most suitable for the location of the park, with the prerequisite that they should be coniferous. A sufficient number of value engineering teams were formed among stakeholders who are experts in trees and parks and can have a say. This team first determined their expectations from the trees, that is, the criteria that the solution of the problem should meet. They then put these criteria in order of importance and calculated the percentages of importance. They quantified the values of the trees to meet these criteria and thus found the satisfaction levels of each tree in terms of meeting the criteria. They also ascertained the purchase costs of each tree sapling. Using all this data, they calculated the value of each tree and decided to plant the tree species with the highest value in the park.

MATERIALS AND METHODS

Value Engineering Method

The selection of trees to be planted in the area designed as a city park will be made with the help of the value engineering method. Value engineering is a teamwork-oriented, organized effort to analyze building features, systems, functions, equipment, and material selections; is designed to solve problems and/or reduce costs while maintaining or improving performance and quality requirements; and performs essential functions at the required performance, quality, reliability, and life-cycle cost. The concept of value is confused with price by many people. However, value is not a concept that can be measured only by the cost or price of that product. Value is meeting people's expectations of a product or service at minimum cost. Since expectations about each product or service cannot be the same for everyone, the concept of value varies from person to person. The highest value is the value that can safely perform the desired functions at the desired time and place and meet the basic quality requirement with the minimum possible total cost. The true value of a product is revealed only by comparing its quality and costs or other characteristics with those of another product that performs the same functions [32].

Value engineering comprises all of the studies carried out by the value engineering team. These studies involve people and technical staff who have a say in the solution of the problem; are in line with customer requests; remove unnecessary functions determined by detailed analyses of products, business processes, or services; and select and implement the least costly alternatives among the alternatives that can solve the problem with various idea generation techniques in line with the criteria determined by the customers as well as the value engineering team by focusing on functions with a high degree of importance. Value engineering is carried out within the framework of a systematic business plan [33]. After the value engineering team members are determined, they start to implement the stages of the business plan; as a result, they choose the most valuable product/service/method.

The sooner the value engineering work is started on a project, the more impact the work will have on the project. In particular, the concept and design stages of the project are the best times to start working. After the design team outlines a project, a multidisciplinary/stakeholder team is formed, the majority of which are not included in the design team, and the project is reviewed and analyzed by this team. The objectives of value engineering are listed below [34].

- Achieve project functions efficiently and at the lowest total cost
- Producing more valuable projects
- Methods that will enable the project to be completed in a shorter time
- Helping to improve building life
- Preventing unnecessary functions and therefore unnecessary costs
- Use the budget and all other resources effectively and efficiently
- Improving project quality
- Producing safer structures
- To eliminate the errors in the project drawing, to draw completely
- All business processes of the project are reviewed, and functions that do not contain value for the customer are removed or new functions are added [35]
- Personnel skills can be revealed by using methods such as creativity, harmony, teamwork, and psychological techniques
- In addition, to produce value-based solutions to any problem encountered during the implementation process of the project, various creativity techniques can be used

The concept of "value" expressed in value engineering can be expressed with the following formulas [36]:

Value = Merit/Cost (1)

Value = Customer Satisfaction/Cost (2)

Value = (Initial Impact to User + Benefit from Goods)/ (Initial Cost + Lifetime Cost) (3)

Value = Benefit (Function)/Cost (4)

Benefit (Function) = Importance × Satisfaction Level (5)

Value engineering is an ideal method for selecting the most suitable materials needed to produce a product from the determined alternatives. There are various studies on material

Figure 1. Location of Sinanoba beach park [42].

selection with the help of value engineering. In one study, partition material was selected for use in wall construction in a reinforced concrete structure with the help of value engineering [37]. In another study, the authors attempted to determine which material/method should be chosen to fill the gap between the shoring wall and the structure using the value engineering method [38]. While in another study, the value engineering method was used to select the exterior cladding material in a building from among sustainable materials according to LEED criteria [39]. Hosseinpour et al. [40] conducted a cost-benefit analysis of the application of urban agriculture in a sustainable park design in their study and benefited from value engineering in this study.

Determination of Tree Type Selection in Park and Garden Construction by the Value Engineering Method: Sinanoba Beach Park Example

Sinanoba, a neighborhood in the Büyükçekmece district of Istanbul Province, is close to the Marmara Sea on the southern side of the district and has following characteristics [41]: a) The southern parts of Büyükçekmece are under the influence of the Mediterranean macroclimate due to the Marmara Sea, b) Covering Terkos Lake in the northern parts are coastal to the Black Sea, they are under the influence of the Black Sea climate. In general, a climate called the "Marmara transition regime" is observed. c) Rainfall can occur in all seasons due to hot and dry summers, warm and humid Black Sea climates in winter, warm summers, and very cold winters. d) Büyükçekmece has its common features from both climate types. An area that does not fall below the soil temperature cutoff is ideal for plants. e) Naturally, oak, beech, and hornbeam can grow in humid places in the region. There are larch and scotch pines among conifers.

Park construction was planned only for the Sinanoba coastal corridor, which is afforested by a concrete road and a single row (Fig. 1). The total area of the park is 3670.86 m², the green area is 3011.564 m², the walking path is 572.096 m², the area where the game groups live is 87.2 m², and the total circumference of the park is 298.21 m [42].

When designing the park, it was decided to plant trees in certain areas. The region is suitable for the survival of many tree varieties; therefore, there are many alternatives. Which of the alternative tree types should be selected can be determined from various perspectives. In this study, trees were planted at an optimal cost so that the trees could meet the projected costs; in other words, the trees could meet the aforementioned requirements, and the value engineering method was applied to achieve this goal.

The problem to be solved in this study is the choice of trees to be planted in a park. The value engineering method was used to solve the problem. For this purpose, first, a value engineering team was formed with representatives from parties and professional groups who could solve this problem or who might be needed to solve the problem. This team consists of five people. These include a landscape architect, a forest engineer, an environmental engineer, a civil engineer, and an owner who wants to build parks and gardens. This team was created to determine the alternatives for all the needs of a park, such as walking paths, perimeter fences, grass to be planted on the ground, and flowers, and to choose the most ideal among these alternatives. However, in this paper, only studies on tree selection are explained as examples to explain the method in detail. First, the team determined the main criterion: Trees should remain green in summer and winter and should not shed their leaves. The team decided that the trees that should be planted be selected among the coniferous species based on the preliminary finding that coniferous trees can meet these criteria and then determine other expectations from the trees, that is, other criteria. After determining which tree species are coniferous and can live in this geographical area, all the criteria determined by the team can be met, and a value analysis study can begin.

For value analysis, first, all the determined criteria were voted upon by the value engineering team and placed in order of importance. After determining where to buy the trees and their prices, the extent to which these tree species met the criteria, that is, the numerical values of their technical and biological characteristics, was determined.

Table 1. Limit values of attributes

Product attributes	Cedrus libani	Cupressus macrocarpa	Picea pungens	Pinus nigra
Average life (year)	1600	1000	400	1000
Reachable height (m)	30	22,5	35	35
The amount it can extend in a year (cm)	100	125	110	100
Leaf shedding rate (%)	0.1	0.1	0.1	0.1
Light liking rate (%)	1	0.5	1	0.5
Min. temperature it can withstand (°C)	-20	-25	-30	-30
Planting range (m)	3.5	5.5	5.5	5
Irrigation request (%)	0.1	0.1	0.5	0.1
Cost (TL/m^2)	261	107	573	132

The trees were selected on the basis of their values, and formula (4) was used for this purpose. To calculate the value, it is necessary to determine the "benefit". The benefit was found with a formula (5). The importance included in the formula was achieved by distributing 100 full points to the attributes normally specified in the product specification or perceived relatively by the customer. The satisfaction level is a value that indicates how satisfied the customer is with the specified qualities of each product. It was found by digitizing between 1 and 10.

As a result of all these calculations, the utility values obtained for each alternative tree species were divided by the costs of the trees, and their values were determined. It was decided to select the tree species with the highest value for the solution of the problem.

Attributes of Trees to Compare

The Value Engineering Team determined the characteristics that can be compared for the selection of trees that need to be planted in the park by the brainstorming method. The specified attributes and limit values of the attributes are given in Table 1.

- Average life (years)
- Reachable height (m)
- The amount it can extend in a year (cm)
- Leaf shedding rate (%)
- Light liking rate (%)
- Min. temperature it can withstand (°C)
- Planting range (m)
- Irrigation request (%)
- Cost (TL/m^2)

Determination of Alternative Tree Types

The Value Engineering Team identified coniferous and purchasable alternative tree species suitable for the geography of the area to be parked, complying with all the determined criteria. The names and characteristics of these trees are described below.

Figure 2. Cedrus libani [45].

Cedrus Libani

Cedru libani, which is a full-bodied, thick-branched, majestic forest tree (Fig. 2) has the following properties [43, 44]: a) Even if a young individual has a pyramidal hill, the hill shape deteriorates over time, becomes flat, and takes the form of an umbrella, b) It is a long-lasting tree genus and live for 1200–2000 years. It is a tree genus that can reach 25–35 meters in length and has a trunk diameter of 2 m. c) As may be inferred from typical instances, it grows in the Mediterranean environment. Nonetheless, it grows better in cool locations because it is a species that can get mite illness. It can dry otherwise. This tree is fond of light.

Cupressus Macrocarpa

Although it is a tree species that is grown on Monterey Island in North America, it is also found in Türkiye and has

Figure 3. Cupressus macrocarpa [45].

following properties [46]: a) It is long-lasting because it can live for 1000 years. It can reach up to 20–25 meters, and the crown width can reach up to 5 meters. b) It is a species that thrives in warm Mediterranean climates. Like light, it can also grow in semi-sunny areas. It is used as a decorative tree, and the curtain is one of the tree species, c) Cupressus macrocarpa leaves, which can form pyramids, are also known as Lemoni Servi because they are yellowish and have the smell of lemon (Fig. 3).

Picea Pungens - Blue Spruce

This tree grows in the high parts of North America and has following features [44]: a) The Blue Spruce species, which can reach 30–40 meters, can live for approximately 400 years. Compared to other spruce species, it is more resistant to drought, b) They become well-developed in cool and temperate climates. These plants are not easily affected by cold, and they are resistant to frost events. It is used in urban green areas because it strongly affects air pollution, c) Since the visual field is aesthetic, these trees are also preferred as Christmas trees (Fig. 4).

Pinus Nigra - European Black Pine

Black pine, which is widely distributed in Türkiye and also grown in Europe has characteristics as follows [46].

Figure 4. Picea pungens [47].

Figure 5. Pinus nigra [48].

a) Larch plants, which can live for an average of 1000 years, can reach heights of up to 20–30 meters, b) They can live in hot and dry places and adapt to all types of climates. These plants can withstand frost events and temperature, c) The leaves are always green. It is tolerant to air pollution, such as blue spruce, and is suitable for urban use (Fig. 5).

Limitations of the Qualifications

The limit values of the qualities of the trees to be compared, determined by the value engineering team, are given in Table 1.

Table 2. Determination of the order of importance of the qualifications with the nominal group technique

VE team attributes	Landscape architect	Forest engineer	Environmental engineer	Civil engineer	Owner	Total	Seq. no
Average life (year)	2	8	7	5	3	25	2
Reachable height (m)	6	7	3	3	4	23	4
The amount it can extend in a year (cm)	5	6	2	2	6	21	6
Leaf shedding rate (%)	7	1	6	1	7	22	5
Light liking rate (%)	4	5	4	4	1	18	8
Min. temperature it can withstand (°C)	3	4	5	6	2	20	7
Planting range (m)	8	2	1	8	5	24	3
Irrigation request (%)	1	3	8	7	8	27	1

Table 3. Determination of importance percentages with the priority matrix method

Attr. seq. No	Attributes	1	2	3	4	5	6	7	8	Total	%	Seq. no
1	Average life (year)		1	1	1	1	1	1	0	6+1	19.4	2
2	Reachable height (m)	0		1	1	1	1	0	0	4+1	13.9	4
3	The amount it can extend in a year (cm)	0	0		0	1	1	0	0	2+1	8.3	6
4	Leaf shedding rate (%)	0	0	1		1	1	0	0	3+1	11.1	5
5	Light liking rate (%)	0	0	0	0		0	0	0	0+1	2.8	8
6	Min. temperature it can withstand (°C)	0	0	0	0	1		0	0	1+1	5.6	7
7	Planting range (m)	0	1	1	1	1	1		0	5+1	16.7	3
8	Irrigation request (%)	1	1	1	1	1	1	1		7+1	22.2	1

Cost values were not directly involved in the problem in the benefit calculation as qualitative properties but were used in the value calculation. Since the planting intervals of the trees are different, the lowest market sales price that can be purchased for each tree was determined, and the tree prices per m^2 of land were calculated and used to solve the problem of calculating a common denominator. When purchasing seedlings, the prices were taken into account, each of which was approximately 200 cm in height.

Rankings and Percentages of Importance of Attributes

The order of importance and percentages of the attributes were determined by the nominal group technique (Table 2) and the priority matrix method (Table 3).

In the nominal group technique, each member of the value engineering team assigned a higher score to the qualifications as required by his/her profession and a lower score to the qualifications he/she found important and insignificant; these scores were subsequently collected, and a general order of importance was created for the whole team. In the priority matrix method, as a result of comparing the qualities by taking into account the order of importance previously determined by the team members, 1 point was given to the more important and 0 to the insignificant; these scores were subsequently summed, and the importance percentages were determined. +1 point has been added to the total score for the comparison of the qualifications with itself.

Satisfaction Levels of the Qualifications

Figure 6a shows the benefit curve plotted for the mean life attribute. On the vertical axis, satisfaction levels are between 1 and 10. On the horizontal axis, the average life quality values were calculated for all the alternative tree species discussed. The performance level with the lowest quality value was matched with 1, the performance value with the highest quality value was matched with 10, and these two coordinates were combined with a linear line. Then, through this line, the satisfaction levels corresponding to the intermediate performance levels of the tree species were determined.

In this example, blue spruce has the lowest satisfaction level, with an average life of 400 years, and cedrus libani has the highest satisfaction level, with a life of 1600 years. In this case, the patients were satisfied with the cupressus macrocarpa shuttle and larch at a level of 5.5 on average. Similarly, the satisfaction levels of all the other qualifications were determined (Fig. 6b–h).

Attribute/Function Matrix

The quality/function matrix was used to calculate the benefits of each tree alternative and its attributes (functions) (Table 4).

The importance of wood alternatives was determined by distributing the previously determined importance percentages of each quality to the ratio of the materials to meet the performance requirements of that quality.

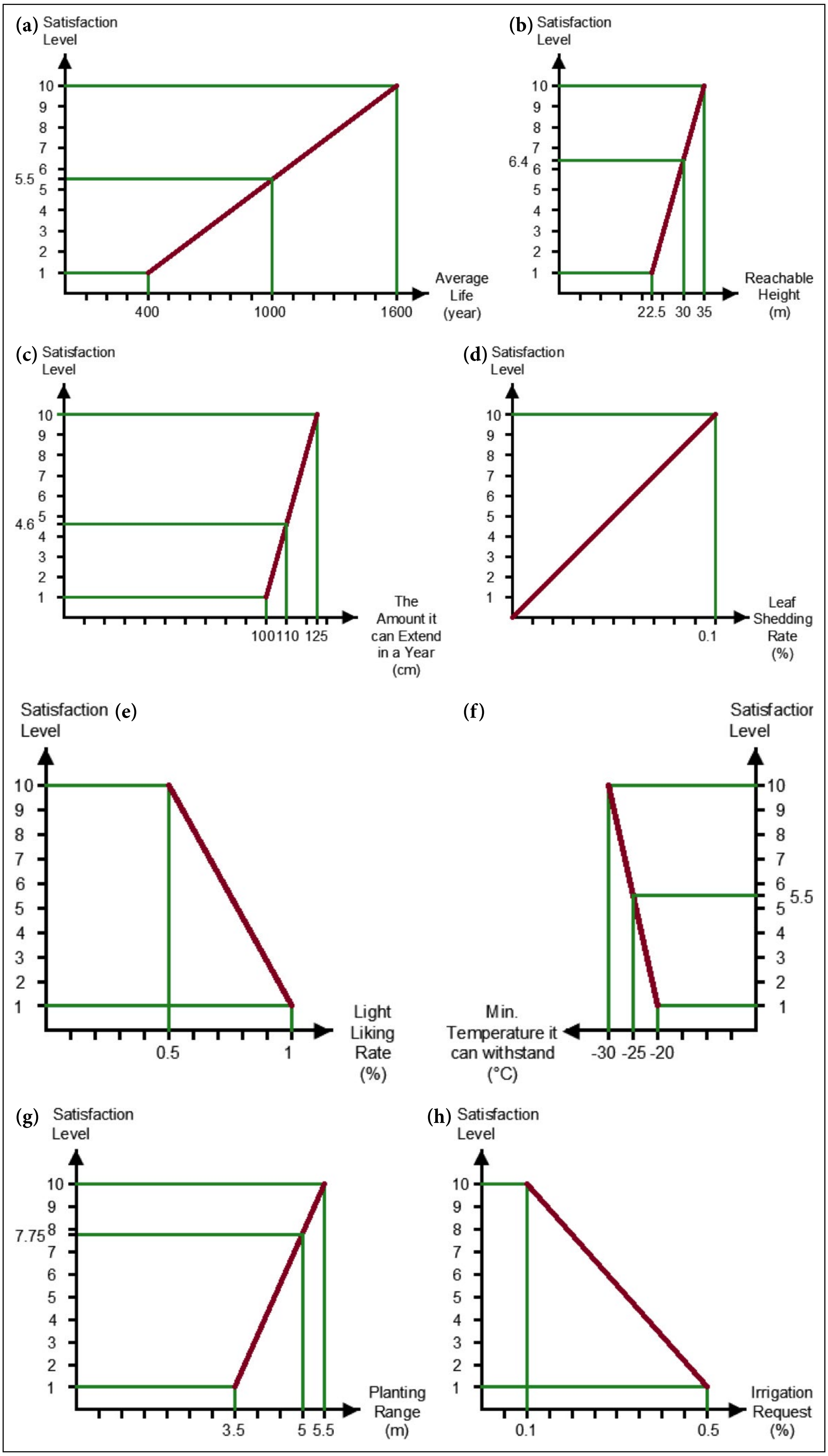

Figure 6. **(a)** Satisfaction level for average life. **(b)** Satisfaction level for reachable height. **(c)** Satisfaction level for the amount it can extend in a year. **(d)** Satisfaction level for leaf shedding rate. **(e)** Satisfaction level for light liking rate. **(f)** Satisfaction level for min. temperature it can withstand. **(g)** Satisfaction level for planting range. **(h)** Satisfaction level for irrigation request.

Table 4. Attribute/function matrix

	Average life	Reachable height	The amount it can extend in a year	Leaf shedding rate	Light liking rate	Min. temperature it can withstand	Planting range	Irrigation request	Total
Cedrus libani									
Importance	7.76	3.40	1.91	2.78	0.47	1.07	3.00	6.47	
Satisfaction level	10	6.40	1	10	1	1	1	10	
Benefit	**77.60**	**21.76**	**1.91**	**27.80**	**0.47**	**1.07**	**3.00**	**64.70**	**198.31**
Cupressus macrocarpa									
Importance	4.85	2.55	2.39	2.78	0.93	1.33	4.71	6.47	
Satisfaction level	5.5	1	10	10	10	5.5	10	10	
Benefit	**26.68**	**2.55**	**23.90**	**27.80**	**9.30**	**7.32**	**47.10**	**64.70**	**209.35**
Picea pungens									
Importance	1.94	3.97	2.10	2.78	0.47	1.60	4.71	2.78	
Satisfaction level	1	10	4.6	10	1	10	10	1	
Benefit	**1.94**	**39.70**	**9.66**	**27.80**	**0.47**	**16.00**	**47.10**	**2.78**	**145.45**
Pinus nigra									
Importance	4.85	3.97	1.91	2.78	0.93	1.60	4.28	6.47	
Satisfaction level	5.5	10	1	10	10	10	7.75	10	
Benefit	26.68	39.70	1.91	27.80	9.30	16.00	33.17	64.70	219.26
Function benefit	**132.90**	**103.71**	**37.78**	**111.2**	**19.54**	**40.39**	**130.37**	**196.88**	

For example, when the importance of cedrus libani for average quality of life is calculated, the importance percentage of the average quality of life determined by the value engineering team is 19.4%. The average life span of the cedrus libani is 1600 years. The sum of the average life spans of all the trees was calculated as follows: (1600+1000+400+1000) =4000 years. In this case, the percentage of importance corresponding to the ratio of cedrus libani to total average life was 19.4 × (1600/4000) = 7.76. Similarly, importance was calculated for all the other tree species. A benefit calculation was performed with the formula (5).

For each tree type, the benefits were calculated by multiplying the importance and satisfaction levels of the quality values corresponding to that tree. These benefits were subsequently collected, and the total benefit was determined for each tree species. In addition, the benefits of each quality value were summed, and the total benefits were found.

RESULTS AND DISCUSSION

Value Calculation

The values were calculated with equation (4). The total benefit of each tree species was divided by its unit cost, and the tree species with the highest value was selected for planting in the park (Table 5).

Considering the tree species deemed suitable for planting in the park and their qualities, it is most appropriate in terms of value engineering to choose cupressus macrocarpa, which has the highest value of 1.96.

Table 5. Value calculation

	Cedrus libani	Cupressus macrocarpa	Picea pungens	Pinus nigra
Benefit	198.31	209.35	145.45	219.26
Cost (TL/m^2)	261	107	573	132
Value	0.76	**1.96**	0.25	1.66

It should be noted here that the tree type with the highest value was determined in line with the preferences and needs of the stakeholders participating in this study, such as their professions, their expectations about the solution, the importance they attach to these expectations, and the tree types they choose. In addition, if these change, the value calculation will also change, so the selected alternative product may also be different.

The concept of value is perceived by most people as the monetary equivalent of the product. However, value is not a concept that can be measured only by cost or price. Value is a personal concept and has a different meaning for everyone. The highest value is achieved by reaching the safest and most cost-effective solution that meets all the expectations of people for the problems they face. The value of a product is revealed only by comparing its quality, cost, or other characteristics with those of one or more products that perform the same functions. The value that one person attaches to one product or to the characteristics of that product may not be the same as another. Therefore, "relative importance" can be mentioned in the concept of value.

Value-based solutions should also be sought for problems encountered in project development or projects. Value engineering is a method developed for this purpose and carried out within the framework of teamwork and a certain business plan. Value engineering is a method that can be applied in all areas of life and tries to increase value without ignoring costs. The value of a project is directly proportional to the owner's or customer's expectations. One of the important issues to be determined here is what the expectation or need is. A project can have many parties/stakeholders. However, these expectations and criteria may have different meanings for the users or technical staff who produce that product. For example, in a construction project, while the user wants all their needs to be met, technical staff expects safety conditions and all legislative requirements to be met, architects want the product to look aesthetic, and manufacturers or owners want to make a profit from the product they produce. These requests often require conflicting decisions. Then, whose criteria and expectations will be taken as the basis? What needs to be done here is to meet the expectations of all parties at an optimum level when producing any product. In addition, there are many alternative materials/methods that can meet all the criteria of stakeholders for solving this problem. Which of these should be chosen? Value engineering can be used to solve problems by overcoming all these problems.

Team selection is very important in value engineering because it will be this team that analyzes the problem, determines the solution alternatives, generates ideas and determines the most valuable solution. When determining team members, the problem to be solved should be addressed in all aspects. There is no exact number recommended for team members. The type of expertise required by the study, the type of project, current conditions, what the needs are, the quality, the time, and the knowledge and experience of the team members are determined by who the team members will be composed of and how many people there will be [49]. Chung et al. [50] in their study, conducted a five-stage value engineering with seven team members in the exterior walls and awning works of a hospital project. Uğural [51] conducted a value engineering study on which wall material would be more appropriate to use in a building and carried out that study with four team members. In addition, different teams or sub-teams can be created to solve different problems. If the number of members in the team is less than needed or if there are no team members at the level of knowledge required by the problem, the solution obtained may be insufficient, incorrect or inapplicable. Conversely, overcrowding of team members can sometimes lead to complexity, conflicts of opinion, and therefore a failure to reach a conclusion instead of a quick solution. For this reason, if it is concluded that a solution can be reached with the knowledge, skills and experience levels of the selected team members after analyzing the problem, the team members are "sufficient". In addition, support from a consultant can be obtained when a problem that requires special knowledge is encountered during the study process. It should not be forgotten that creating a value engineering team and getting services from them for a certain period of time also requires a certain budget. Having more team members than needed also means an unnecessary budget increase. In this study, the problem was analyzed, and five team members were selected from the fields of science and knowledge levels required by the solution of the problem. There was no need for support from a consultant during the study process.

While applying the value engineering method for the selection of trees discussed in this study, the criterion proposed by any stakeholders in the value engineering team was not prioritized, and the request of each stakeholder was included in the problem in proportion to the importance of that criterion. Since the value engineering method is not cost-based, but a value-based method, the alternative with the highest value, including the cost, has been chosen as the solution to the problem, not the alternative with the lowest cost.

In the criteria considered, the purchase costs of the seedlings were taken into account as the initial investment cost. However, criteria such as irrigation needs and defoliation rates were added to the problem, and the irrigation and maintenance costs that trees may need throughout their life cycle were indirectly included in the importance calculations.

There are studies available on the selection of trees to be planted in city parks and on the sides of the streets using various methods. In one study, trees that should be planted in various streets and parks in Hefei were selected from alternative tree species in the inventory using the Analytical Hierarchy Process (AHP) method and expert knowledge approach [52]. In a study, Sjöman et al. [53] examined the tree species growing in certain regions of various countries with similar climatic and field conditions by conducting the field research, and concluded that the 27 species of trees they identified in this research could live in other similar climatic and field conditions, and that the planted tree species could be diversified. In a study of trees planted in the city of Toronto, Canada, surveys were conducted with landscape architects, non-profit organizations, retail nurseries and garden centers, and municipal forestry staff in Toronto, and it was observed that each group chose the tree to be planted with different criteria and determined the type of tree to be planted with their own experience [54].

CONCLUSION

In this study, it was desirable to build a city park. Many needs, such as roads, perimeter fences, grass, flowers, and trees, have been identified for this park. For these reasons, there are many accessible alternatives on the market with different features and prices. Which of these should be selected? A value engineering study was conducted on this subject. Value engineering studies conducted only for the selection of tree species are explained in detail in this study as an example. First, a value engineering team consisting of professional groups and owners who can have a say in the construction of the park was formed. A list of criteria, including expectations about the tree species, was determined, taking into account the conditions required by the geographical region where the park will be built, customer requests, and technical requirements. Considering these criteria and costs, a value calculation was performed, and it was decided that the "cupressus macrocarpa", which has the highest value, would be planted in the park.

In this study, a solution was sought through value engineering, as an objective selection method, in a way that will meet all the criteria determined by the team members selected considering that they can contribute to the solution of the problem for the tree species to be planted in city parks. This study addressed the benefits of value engineering by demonstrating a case study on selecting tree species in parks. Applying the value engineering norms in parks can yield several benefits to explore the most appropriate alternative in terms of average life, height, extension amount, leaf shedding rate, light, temperature, planting, irrigation and cost. The implications of this study is crucial for different stakeholders, such as policy-makers, municipalities, contactors and designers. For future studies, it may be suggested to try to solve the problem by increasing alternatives with more comprehensive criteria and much more tree species.

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.

USE OF AI FOR WRITING ASSISTANCE

Not declared.

ETHICS

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

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Research Article

Bibliometric profile of research on ecological footprint

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ABSTRACT

The ecological footprint is an indicator of environmental impact and has become a significant research topic in recent years. It plays an important role in raising awareness about minimizing environmental problems by determining the extent of damage to the ecosystem. The ecological footprint is a valuable tool for researchers to assess the level of environmental damage and identify its causes, with the ultimate goal of promoting sustainability. This study aims to conduct a bibliometric analysis of scientific publications on the ecological footprint in the international arena. The study is descriptive and employs the scanning method. The researchers searched for studies published between 2010 and 2021 using the key concept of 'Ecological footprint' in the database. The bibliometric characteristics of 2748 publications scanned in the Web of Science database were determined. The research data were analyzed based on the number of publications per year and country, the most productive authors and journals, authors' h-indexes, most cited authors and journals, distributions by most cited references, and some relationships between these variables. The data reveal the interdisciplinary importance of the subject.

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INTRODUCTION

Due to population growth and rapid economic development, natural resource consumption is increasing, disrupting the balance of ecosystem capacity and causing environmental problems [1, 2]. Additionally, it is evident that the consumption of significant quantities of natural resources through agriculture, industrialization, deforestation, and mining has a detrimental impact on the environment [1]. Environmental issues, such as global warming, ozone depletion, and the greenhouse effect, are examples of negative effects. Factors that harm the environment, such as soil and water pollution, and destruction of ecosystems, should not be overlooked [2]. Raising awareness about the growing environmental problems and explaining them with measurable magnitudes is crucial. The concept of 'ecological footprint,' introduced by Rees in 1992, provides a way to quantify environmental issues. Its purpose is to ensure a protected environment for future generations and promote sustainability. Durkaya [3] stated that to keep environmental sustainability in the ecosystem under control, attention should be paid to environmental problems. Recent studies have highlighted the ecological footprint as an indicator of environmental degradation [4, 5]. Additionally, the studies include the most significant factors that determine the ecological footprint.

The use of unsustainable natural resources can negatively impact a country's biological capacity. When humans exceed the biological capacity of nature and consume more resources than can be replenished, it can lead to ecological vulnerability [4]. Countries have a global impact on the

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ecosystem, but this impact may not be immediately apparent. The degradation of the environment is influenced by higher population density, increasing energy demand, urbanization, and rapid industrial development over time. Economic growth leads to increased use of natural resources, causing pollution that poses a significant threat to the environment. Therefore, the ecological footprint helps countries evaluate their ecological resources [6]. An ecological footprint is a tool used to measure the impact of human activities on the environment. No changes in content were made. It calculates the amount of natural resources used based on global, regional, local, and personal supply and demand [7]. Therefore, the area of the ecological footprint, which is a calculable size; It is a quantity that depends on population size, material living standards, the technology used, and ecological productivity [8]. Ecological footprint calculations consider six types of land use for consumption distribution: agricultural lands, pastures, forests used for fuel and consumption, fishing areas, construction areas, and forest areas required for carbon emission capture. Durkaya [3] stated that when all the countries of the world care about the six components of the ecological footprint separately, they can secure their future by using all the resources in the ecological system more accurately. Furthermore, taking into account the ecological footprint as a whole is predicted to mitigate the risks associated with ecological deficits. The literature contains various bibliometric studies on the ecological footprint. Yang and Meng [9] compared the hotspots and boundaries of articles on the topic of ecological footprints in China and internationally from 2000 to 2017. A total of 2322 articles were found in the English literature using the WoS database, while 1925 articles were accessed in the Chinese literature through the Chinese national information infrastructure database. Ulucak and Erdoğan [10] conducted a bibliometric analysis of 2582 articles on ecological footprint in the Web of Science database. The analysis revealed that there were no limitations on the specific area or period of the articles.

In their research on the environmental footprint family, Wang et al. [11] conducted a comparative bibliometric analysis of Chinese and foreign articles. The study compared and analyzed two data sets covering 1103 Chinese and 6011 foreign articles on environmental footprints and footprint families between 1996 and 2019 using bibliometric analysis. Xie et al. [12], used various footprint indicators to investigate the environmental footprint family domain's overall appearance through bibliometric analysis. They reviewed all 6680 articles from the Web of Science Core Collection database between 1996 and 2018 and examined research topics in the field of environmental footprint family. The study employed bibliometric analysis to identify the top 16 journals, 15 academicians, 19 most productive institutions, and 15 influential countries/regions.

Ecological footprint calculations are crucial for a country's development and require economic and ecological sustainability. An ecological footprint measures human consumption of natural resources and their impact on the ecosystem. It provides concrete data for analysis. Calculating ecological footprints is essential for obtaining information to ensure sustainability. Therefore, the ecological footprint has become a popular research topic in recent years. Studies are conducted in the fields of education, engineering, and economy to measure the impact of human activities on the environment. The ecological footprint is an important concept that draws attention to the increasing environmental problems and provides a measurable way to express them. However, no bibliometric analysis has been found in the eleven-year period regarding the ecological footprint, which is an important issue in the literature. Therefore, we determined the bibliometric properties of publications related to this subject in the Web of Science database. The objective of this study is to comprehensively examine the results of all published studies on ecological footprint. The study analyzes the relationships between the number of publications of studies on ecological footprint by year, the number of publications by country, the most productive authors and journals, h-indexes of authors, the most cited authors and journals, and their distribution according to the most cited sources. The bibliometric analysis of research on ecological footprint provides a situational assessment for new researchers interested in this subject. Therefore, researchers who wish to highlight the issue of ecological footprint should address the deficiencies or explore different aspects of the subject, rather than repeating similar research on the topic.

This study conducted a bibliometric analysis of ecological footprint studies published in the Web of Science database between 2010 and 2021. The research aimed to answer the following questions:

1- What are the Characteristic Features of the Selected Publications?

2- What are the Characteristics of the Selected Authors?

MATERIALS AND METHODS

The study employed bibliometric analysis, a quantitative research method. The bibliometric methodology involves using quantitative methods on bibliometric data [13]. The bibliometric method is a quantitative analysis of publication characteristics, including subject, author, publication information, and cited sources, produced by individuals or institutions in a specific period and region within a particular field [14–17]. Bibliometric analysis is a rigorous and popular method for researching and analyzing large volumes of scientific data. It is used to decipher and map the developmental details of cumulative scientific knowledge by meticulously making sense of large volumes of unstructured data [18]. The main purpose of the bibliometric analysis is to reveal the general trends, scientific progress, and the current situation of publications in a particular field. Two important features of bibliometric analysis are performance analysis and scientific mapping of publications in a specific field [19].

Table 1. Data collection criteria

Criterias	Data	
Database	Web of Science Core Collection	
Keywords	"Ecological footprint"	
Publication date	2010–2021	
Language	English	2628
	Spanish	51
	Portuguese	18
	Chinese	16
	Others	35
Document type	All types	
Access type	All types	

Table 2. Descriptive characteristics of publications by country

No	Country	Citation (n)	Average citation per publication ($\bar{x}$)	h-index
1	China	13503	17.87	55
2	USA	9704	33.62	53
3	Türkiye	7015	35.92	46
4	Australia	4899	46.58	32
5	Pakistan	3730	30.89	35
6	England	3690	30.54	32
7	Netherlands	3447	45.22	31
8	Spain	3425	19.29	31
9	Italy	2691	19.72	32
10	Germany	2608	24.71	27

Bibliometric analysis was utilized to examine publications on the ecological footprint. The research data were obtained from the Web of Science database on June 3, 2022. A total of 2,748 publications between 2010 and 2021 were analyzed using the Web of Science database. The dataset was created by searching the Web of Science database using the keyword 'ecological footprint'. The purpose of utilizing a broad term like 'ecological footprint' is to access all published research across various disciplines.

The bibliometric analysis utilized various variables such as the distribution of publications by year and country, the most published authors, the h-index, citation density, best journal, and keywords. This analysis serves as a guide for field experts and researchers in a particular subject area. The study examined publications related to the ecological footprint using the Web of Science (WoS) database as the main source for publication searches. This database is preferred because it provides easy access to higher education institutions, a wide variety of data options, and includes top-level articles from respected journals. The Web of Science (WoS) database includes over 21,100 peer-reviewed scientific journals published worldwide in over 250 disciplines of science, social sciences, arts, and humanities. The database includes the Science Citation Index Expanded, the Social Sciences Citation Index, the Arts & Humanities Citation Index, and the Emerging Sources Citation Indexes [20]. After establishing the criteria for data collection in the bibliometric analysis, the results are presented in Table 1. Table 1 shows that between 2010 and 2021, 2628 publications were in English, making it the most commonly used language. A bibliometric analysis was conducted on all document and access types.

The research data were collected from the WoS database based on predetermined criteria. The data was then formatted and analyzed using Microsoft Excel and VOSviewer. Microsoft Excel was used to encode, edit, and analyze data, including publication number, author, journal, keywords, number of referenced references, and number of citations. This process was completed independently by two authors, and any differences identified in the dataset were discussed until a consensus was reached. VOSviewer is a Java-based program that creates maps using bibliographic data and allows for their visualization and exploration [21]. This research utilized VOSviewer to analyze and visualize bibliographic data, including publications, co-authorship between countries, co-citation, and keyword reproducibility. Microsoft Office Excel is a program used for mapping and analyzing geographic data from publications around the world. The WoS database also utilizes it to obtain additional information about publications, such as the h-index and the journal's impact factors.

RESULTS AND DISCUSSION

The ecological footprint is an important factor in addressing environmental issues. Numerous scientific studies on the ecological footprint have been conducted and can be found in the Web of Science database. Most of these studies focus on the impact of the ecological footprint on sustainability and the calculation of the environmental Kuznets curve using the ecological footprint. This section presents an analysis of publications on ecological footprint between 2010 and 2021. The WoS database research revealed a total of 2,748 publications by 6,944 authors published in 351 publishing houses. The relevant publications obtained from the WoS database are discussed below.

The Analysis Of Publications And Authors On Ecological Footprint

Characteristic Features of the Selected Publications

The distribution of publications by country was evaluated. It was found that research on ecological footprint has been carried out in China with a maximum of 786 publications. The highest number of publications was found in the USA (305) and Türkiye (196). Figure 1 shows the countries with more than 20 publications between 2010 and 2021.

Figure 2 evaluates the distribution of the number of publications and citations by year. The data obtained from the WoS database shows a stable increase in the number of publications related to the ecological footprint until 2018, with no significant increase. However, after 2018, there has been

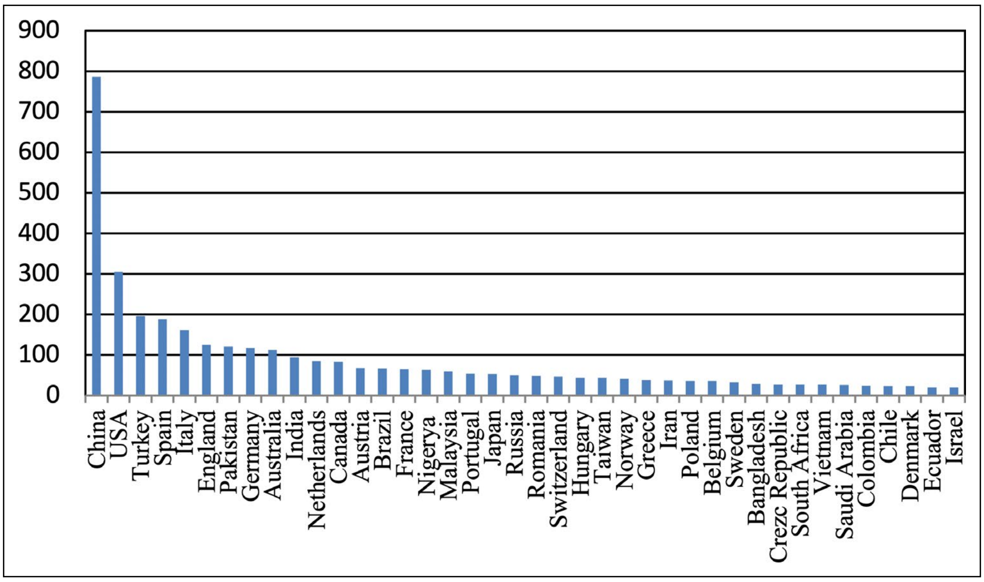

Figure 1. Distribution of publications by country.

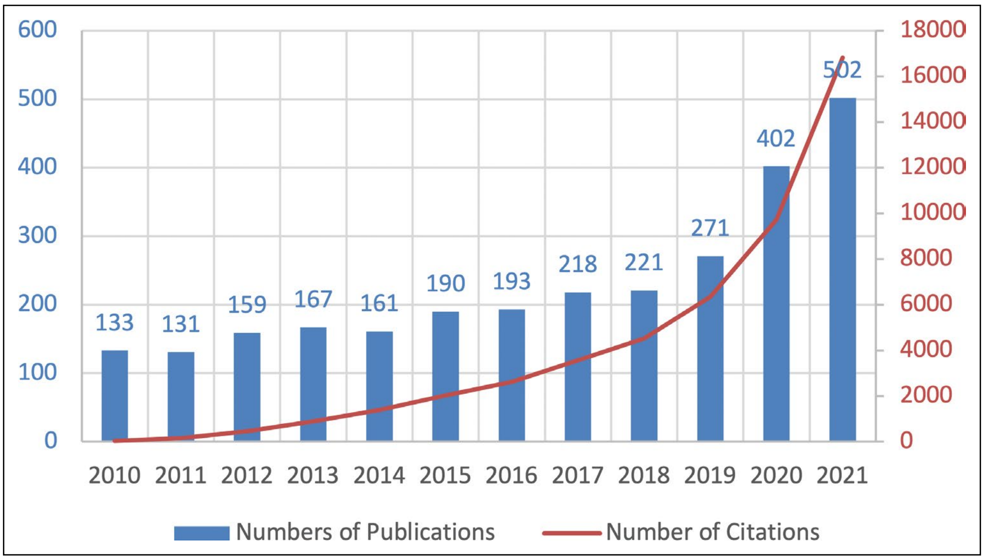

Figure 2. Distribution of publications and citations by year.

a linear increase in the number of publications related to the ecological footprint. The chart shows a 48% increase in publications on the subject between 2019 and 2020, and a 24% increase between 2020 and 2021. The reason for the increase in the number of publications on the topic of ecological footprint between 2019 and 2020 can be attributed to environmental problems and global climate change.

Figure 2 shows a parabolic graph of the increasing number of citations of the publications between 2010 and 2021. During this period, the number of citations to publications has consistently increased. In publications focused on the ecological footprint, the number of citations in 2021 was the highest at 16,817.

Table 2 presents the descriptive characteristics of publications, including the number of citations, average citations per publication, and h-index, analyzed by country. The countries with the highest number of citations are China (13503), the USA (9704), and Türkiye (7015), respectively. China, the USA, and Türkiye have the highest number of citations with 13503, 9704, and 7015 respectively. Meanwhile, Australia and the Netherlands have the highest average number of citations per publication with $\bar{x}$=46.58 and $\bar{x}$=45.22 respectively, followed by Türkiye with $\bar{x}$=35.92. China, America, and Türkiye have the highest h-index scores of 55, 53, and 46, respectively. According to Kızılöz [22], the number of citations received by scientific articles is an indicator of how much attention an article has received from other articles. The number of citations received by scientific articles is an indicator of how much attention an article has received from other articles. High citation numbers are expected to reflect a greater level of attention. According to Yang ve Meng [9], the number of citations an author receives from their articles is a key factor in determining their influence. Citation analysis is crucial for bibliometric applications as it indicates an author's academic influence in the field.

Table 3. Performance of the 10 most productive journals

No	The international journal	TP[a]	IF[b]	PP[c]
1	Environmental Science and Pollution Research	198	4.223	0.0720
2	Journal of Cleaner Production	163	9.297	0.0574
3	Ecological Indicators	158	4.958	0.0575
4	Sustainability	155	3.251	0.0564
5	Science of The Total Environment	55	7.963	0.0200
6	Journal of Environmental Management	40	6.789	0.0145
7	Advanced Materials Research	38	30.849	0.0138
8	Ecological Economics	37	5.389	0.0134
9	Environment Development And Sustainability	31	3.219	0.0112
10	Sustainable Cities and Society	26	7.587	0.0094

a: The total publications of the journal during 2010–2021 period; b: The international journal's impact factor is from the respective official website in 2020; c: Percent point.

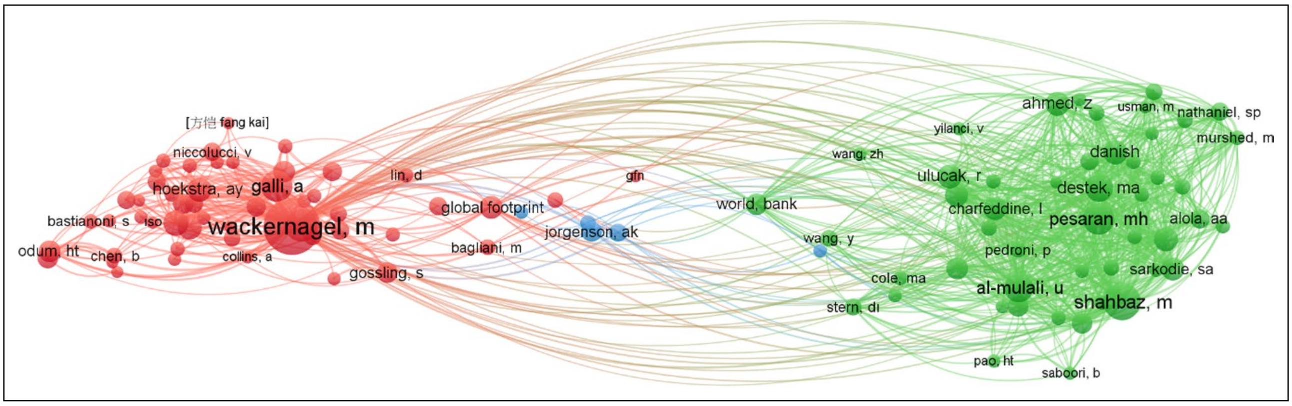

Figure 3. Map of common citations of references used in the research of ecological footprints (authors with more than 100 citations).

Table 3 displays the top 10 journals that have published the most articles on the ecological footprint internationally from 2010 to 2021. One of the main journals that includes studies in all areas of environmental science with an interdisciplinary perspective is 'Environmental Science and Pollution Research.' Its impact factor is 4.223, which is lower than the impact factor of other journals in the top three rankings. Therefore, the journal is preferred and has the highest total number of publications between 2010 and 2021. Furthermore, the journal's open access policy and prompt response to researchers during the publication process may also contribute to its popularity. The research articles on ecological footprint in the Web of Science database are ranked based on their impact factor as follows: Based on the impact factor, 'Advanced Materials Research' is ranked first with 30,849, followed by 'Journal of Cleaner Production' in second place with 9,297, and 'Science of the Total Environment' in third place with 7,963. A journal's impact factor is the average number of citations that papers published in the previous two years received in the current year. The impact factor of each international journal was obtained from the relevant official website in 2020. 'Advanced Materials Research' is a comprehensive periodical that covers both theoretical and practical research in materials engineering. This journal accepts publications from various disciplines to explore the technical aspects of the ecological footprint issue within the context of sustainable development, natural resources, and renewable energy resources.

The remaining journals listed in Table 3 are international, interdisciplinary publications with a citation index of 3.219. These journals cover topics related to environmental and sustainability research and practices on a global scale.

Table 4 presents the 10 most cited publications on ecological footprint. The top three, published in 'Science', 'Journal of Cleaner Production', and 'Annals of Tourism Research', respectively, received the most citations. Additionally, 3 of the 10 most cited studies related to the subject were published in 'Ecological Indicators', indicating the journal's effectiveness in this field.

Figure 3 shows the bibliometric map view of the common citations of the references used in the Ecological Footprint publications. Bibliometric mapping is a recent method in bibliometric analysis that visually represents the relationship between different disciplines, specialties, documents, and authors [33]. Similarly, analyzing commonly cited references is frequently utilized in bibliometrics [34].

Table 4. The 10 most cited publications on the research of ecological footprints

No	Title	Authors	Journal	Wos citation count (n)
1	Humanity's unsustainable environmental footprint	Hoekstra and Wiedmann [23]	Science	518
2	A Review of footprint analysis tools for monitoring impacts on sustainability	Cucek, Klemes and Kravanja [24]	Journal of Cleaner Production	490
3	Sustaınable tourism: Research and reality	Buckley [25]	Annals of Tourism Research	469
4	Integrating ecological, carbon and water footprint into a “footprint family” of indicators: Definition and role in tracking human pressure on the planet	Galli et al. [26]	Ecological Indicators	458
5	Urban ecology and sustainability: The state-of-the-science and future directions	Wu [27]	Landscape and Urban Planning	425
6	Investigation of environmental Kuznets curve for ecological footprint: The role of energy and financial development	Destek and Sarkodie [28]	Science of the Total Environment	395
7	Review of sustainability indices and indicators: Towards a new City Sustainability Index (CSI)	Mori and Christodoulou [29]	Environmental Impact Assessment Review	379
8	Affluence drives the global displacement of land use	Weinzettel et al. [30]	Global Environmental Change-Human and Policy Dimensions	373
9	Accounting for demand and supply of the biosphere's regenerative capacity: The National Footprint Accounts' underlying methodology and framework	Borucke et al. [31]	Ecological Indicators	352
10	Investigating the environmental Kuznets curve (EKC) hypothesis by utilizing the ecological footprint as an indicator of environmental degradation	Al-Mulali et al. [32]	Ecological Indicators	349

The bibliometric mapping method employs circles of different colors to represent clusters. The size of each circle corresponds to the citation frequency of the reference, with larger circles indicating higher citation frequency. Lines are used to show the relationship or connection between circles and clusters, with closer proximity indicating a stronger relationship between the two articles. The line connecting the two circles indicates that both articles were cited in one publication. The length of the line indicates the strength of the connection between the two articles [21, 35].

Figure 3 displays a map of common citations among authors with more than 100 citations. The red, blue, and green color clusters indicate that the references used in the ecological footprint study are grouped into three categories. The common citation density among the authors is primarily in the red and green color clusters. Figure 3 shows Wackernagel in the foreground of the red cluster and Shahbaz in the foreground of the green cluster. In the blue color set, although the authors have a low common citation density, there is a relationship between them in terms of common citation links. Jorgenson is in the foreground in the blue cluster.

Figure 4 displays the hotspot networks of keywords in publications related to the ecological footprint in the Wos database. The analysis reveals that 'ecological footprint' is the most frequently used keyword in all publications. Additionally, the network of keywords includes terms such as 'water footprint', 'ecological capacity', 'municipal solid waste', 'ecological deficit', 'global warming', 'emergency', and 'greenhouse gases'. Upon analyzing the distribution of keywords by year, it is evident that the words have become more diverse and the relationship network has expanded.

The research articles in the Web of Science database on ecological footprint were analyzed to determine the most frequently used keywords. Table 5 displays the keywords that were used in publications 50 or more times, along with their frequency of use.

Electronic databases and search engines in journals use keywords to locate articles on specific subjects. Therefore, it is crucial to select effective keywords that accurately reflect the research topic of the article. Keywords should be commonly used terms in the research field that are specific to the article. Additionally, it is important to select appro-

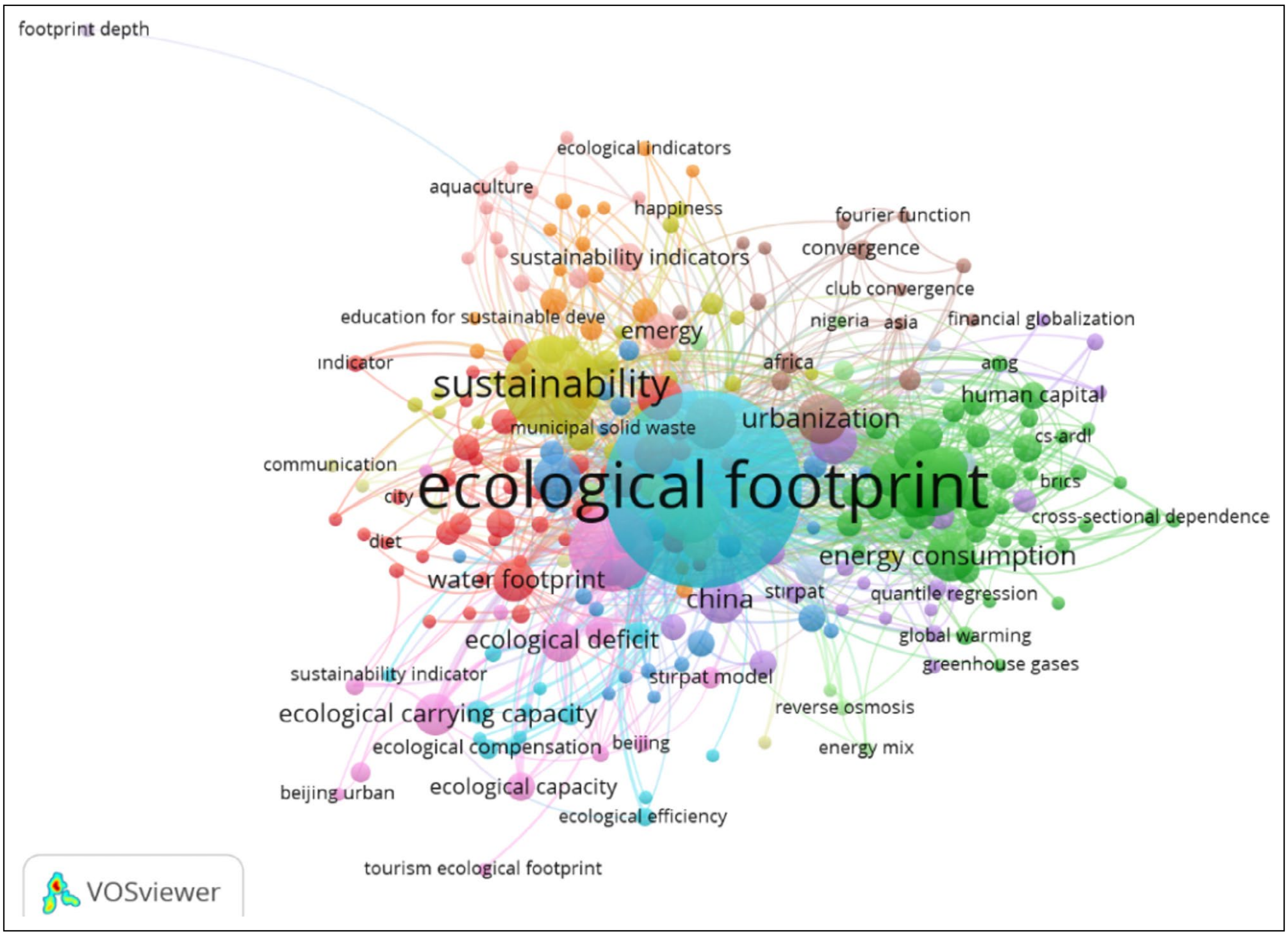

Figure 4. Bibliometric network analysis of keywords used in scientific publications on ecological footprint between 2010–2021.

Table 5. Information on keywords between 2010 and 2021 (50 or more repeats)

No	Keywords	Frequency	Total link strength
1	Ecological footprint	1061	612
2	Sustainability	253	178
3	Sustainable development	201	157
4	Economic	124	133
5	Carbon footprint	99	101
6	Biocapacity	73	95
7	Urbanization	68	87
8	Energy consumption	68	79
9	Renewable energy	67	72
10	Life cycle assessment	61	43
11	Environmental sustainability	60	58
12	China	60	52
13	Environment	56	45
14	Ecological carrying capacity	50	58

priate keywords to assist researchers in locating relevant information on the topic [36]. Table 5 shows that the most commonly used keywords are 'ecological footprint', 'sustainability', and 'sustainable development'.

Characteristics of Selected Authors

In scientific research, the productivity of authors can be analyzed by examining the number of publications they have produced. When conducting a bibliometric analysis on ecological footprint, the study determined the number of publications by the 10 most productive authors, the average number of citations per publication, the h-index, and research areas (Table 6). Out of the 2748 publications in the WoS database, Galli and Alessandro were identified as the most productive authors with 35 publications. These authors also have the highest average citations per publication. The research areas of the most productive authors were found to be Environmental Science and Ecology. The top ten authors ranked by average number of citations per publication are Galli and Alessandro in first place with 77.57, followed by Ahmed and Zahoor with 58.65, Wackernagel and Mathis with 52.5 in third place, and Lin and David with 43.84 in fourth place. The authors with the highest h-index in the top ten are Galli and Alessandro with 23 and Wackernagel and Mathis with 15.

CONCLUSION

Bibliometrics is the study of objectively derived and quantitatively categorized research topics in published studies across different disciplines. It involves examining, rearranging, and creating patterns from a scientific perspective. In

Table 6. The Top 10 Most productive authors

No	Authors	Publication (n)	Average citation per publication ($\bar{x}$)	h-index	Research area
1	Galli, Alessandro	35	77,57	23	Environmental Sciences Ecology
2	Li, Ying	25	8,8	7	Civil Engineering & Architecture
3	Wackernagel, Mathis	24	52,5	15	Sustainability
4	Marrero, Madelyn	21	20,43	10	Building Construction
5	Lin, David	19	43,84	14	Sustainability
6	Yang Yi	19	15,32	11	Econ & Management
7	Alola, Andrew Adewale	18	35,22	12	Accounting & Finance
8	Narodoslawsky, Michael	18	17,33	10	Sustainability
9	Ahmet, Zahoor	17	58,65	14	Econ & Management
10	Bekun, Festus Victor	17	38,18	11	Logistics Management

recent years, the use of bibliometric analysis has become increasingly prevalent in all fields of science. This study examines the issue of ecological footprint, a measurable indicator of environmental problems, using bibliometric analysis. Ecological footprint represents the use of the environment and natural resources to ensure economic and ecological sustainability, making it a crucial research topic today. Ulucak and Erdem [37] state that environmental factors play a crucial role in the growth process of developing countries. In other words, a country's development level is influenced by its ecological footprint. Tosunoğlu [38] states that ecological footprints vary due to differences in populations and consumption habits among countries. Given that environmental problems are multidimensional and irreversible, international efforts should be increased.

Nations have recognized the need for increased international cooperation to address environmental problems with a holistic approach in order to reduce the Ecological Footprint. Therefore, ecological footprint research is crucial to draw attention to the growing environmental problems and express them with measurable sizes. The bibliometric analysis method was used to analyze studies on ecological footprint between 2010 and 2021, utilizing the WoS database on an international platform. [39] The purpose of this study is to analyze the scientific cooperation structure of publications on ecological footprint using bibliometric analysis. A total of 2748 publications were analyzed by scanning the Web of Science database, and trends over the past 11 years were identified. According to the findings obtained as a result of the examinations, the distribution of the number of publications in the WoS database on ecological footprint by country is as follows. China ranks first with 786 publications, followed by the USA with 305 publications, and Türkiye in third place with 196 publications. It is worth noting that Türkiye is included in the ranking.

Upon examining the distribution of publications by year, it was found that there was a maximum increase of 48% between 2019 and 2020, while there were no significant increases in the number of publications prior to 2018. On the other hand, the distribution of the number of citations by year shows a constant increase in a parabolic manner. Additionally, it is observed that the highest number of citations received in publications on the subject of ecological footprint was in 2021, with a value of 16817. Australia has the highest average number of citations per publication, while China has the highest H-index.

Environmental Science and Pollution Research is the top journal in terms of the number of articles published on the international platform between 2010 and 2021, with a total of 198 publications. However, its impact factor is 4.223. The impact factor of this journal is lower than that of other journals in the top three rankings. However, it is preferred due to its complete open access policy and quick turnaround time for research publication. Among the top 10 journals, the 'Advanced Materials Research' journal has the highest number of published articles on the topic of ecological footprint.

The top three most cited publications on the ecological footprint in the WoS database are 'Science', 'Journal of Cleaner Production', and 'Annals of Tourism Research'. Additionally, three of the top ten most cited studies on the subject were published in the Ecological Indicators Journal. The data suggests that the journal is effective in this field. The reason for the high number of citations may be attributed to the impact of ecological footprints on sustainability. Furthermore, the top 10 most cited publications cover various determinants of water, carbon, and other environmental components related to the ecological footprint.

The authors who received more than 100 citations related to the ecological footprint in the WoS database are linked through common citations, which are grouped into three clusters: red, blue, and green. The authors' common citation density is highest in the red and green color clusters, while it is low in the blue color cluster. This suggests that the authors in the blue color cluster are less connected in terms of common citation links.

Upon analyzing the hotspot networks of keywords in publications related to ecological footprints in the WoS database, it was found that the term 'ecological footprint' was the most frequently used keyword in all publications. Furthermore, Figure 4 illustrates the utilization of keywords in the time zone view of the keyword network, including water footprint, ecological capacity, municipal solid waste, ecological deficit, global warming, emergency, and greenhouse gases. The publications' keywords have diversified, and the network of relations has expanded up to the present day. The three most frequently used keywords in publications in the WoS database are ecological footprint, sustainability, and sustainable development.

This study found that numerous authors from various disciplines have published works on the ecological footprint, which is a measure of environmental impact. Based on the bibliometric analysis, it is evident that China has the highest number of publications and citations on this subject. This bibliometric analysis study has several limitations. Firstly, the inclusion criteria have been rigorously determined. Although the WoS database is extensive, there is a possibility that some publications may have been overlooked.

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.

USE OF AI FOR WRITING ASSISTANCE

Not declared.

ETHICS

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

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Research Article

The relationship between industry 5.0 Process and ESG process: A qualitative analysis in the context of Türkiye's BIST Sustainability 25 Index white good sector

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ABSTRACT

This study aims to determine the relationship between Industry 5.0 and ESG (Environmental Social Governance) processes. In addition, this study aims to reveal how this relationship is evaluated within the scope of Vestel and Arçelik enterprises in the white goods sector within the scope of the BIST (Borsa Istanbul) Sustainability 25 Index in Türkiye. For this aim, the relationship between Industry 5.0 and ESG processes was first explained using document analysis, one of the qualitative analysis techniques. Then, descriptive content analysis, which is also one of the qualitative analysis techniques, was used to examine the latest annual reports of Vestel and Arçelik, which are in the white goods sector within the scope of the BIST Sustainability 25 Index in Türkiye, published in 2022. For Industry 5.0, Industry 4.0, environment, employees and society, and finally, the resilience of businesses components were considered, while for the ESG process, environmental, social and governance components were emphasised. NVivo (version 14.23.2) software was used for the analysis. As a result of the study, it was determined that there is a close bidirectional relationship between the components in the Industry 5.0 process and the components in the ESG process. In other words, it can be said that investing in ESG processes will contribute positively to the Industry 5.0 process and investing in the Industry 5.0 process will contribute positively to the ESG process. Within the scope of Industry 5.0 and ESG processes, Vestel and Arçelik have similar studies. In addition, this study offers suggestions for developing practices for the ESG process by adapting to technological change.

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INTRODUCTION

The industrial revolutions, reported to have started after James Watt discovered the steam engine in the 1700s, continued with the Industry 4.0 process in 2011. The Industry 4.0 process has recently started to be studied together with the digital transformation process of businesses. It has even been referred to as the digital transformation of businesses rather than the definition of the Industry 4.0 process. Industry 4.0 is focused on increasing collective productivity and performance through collaboration between devices and software using machine learning (ML) [1].

In the industrial revolutions prior to Industry 4.0, there was unilateral automatisation, that is, the process of doing business by giving commands from humans to machines or oth-

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er systems. In unilateral automatisation, no data is obtained from machinery, equipment, software or employees within the business. It is thought that the most important difference that distinguishes the Industry 4.0 process from other industrial revolutions is the transition to bilateral automatisation [2]. Bilateral automatisation refers to processes that can be commanded from human to machine, machine to human, and machine to machine. In bilateral automation, it is possible to acquire data from machines, equipment, software or employees within the business. The knowledge that emerges from analysing the data obtained is shared with the systems that need it, and a data and knowledge cycle is established. In this way, benefits such as predictive maintenance work on machines, increasing product quality, automatically determining the location of inventories, assisting decision making, sustainable supply chain and human – technology collaboration are provided. These benefits also enable savings in labour and energy costs [2]. These processes are usually automated thanks to related software [2]. For example, thanks to the Internet of Things (IoT) infrastructure, the actions that arise from analysing the data collected from the production environment with software can be performed by actuators without human intervention [2].

The concept of employee and human (society), which was not fully explained in the Industry 4.0 process, started to be explained in the Industry 5.0 process, called the industrial revolution after the Industry 4.0 process. While Industry 4.0 aims to use machines and systems most efficiently, Industry 5.0 focuses on bringing back the human factor [3]. It emphasises a system based on robot-human collaboration that supports people to work more efficiently with technology support [4]. This collaboration can be explained with a human-centred approach. The human-centred approach represents a systematic transformation in industry that goes beyond economic and production outcomes and profoundly impacts civil society, governance structures and human identity [5].

In line with the principles of Industry 5.0, the Japanese government has initiated the idea of Society 5.0, which represents a human-centred society that balances economic development with solving social problems using a system that integrates the cyber and physical environment [6]. Society 5.0 promotes physical and cyber environment collaboration to solve employee, production and sustainability issues and social issues [7]. Related to this, it is noted that Society 5.0 and the United Nations Sustainable Development Goals share a common vision of creating a sustainable and inclusive future for all. Thus, the Industry 5.0 process is defined as an industrial revolution that can be considered a complement to the Industry 4.0 process, which explains issues such as employees and people, the environment, and the resilience of businesses with technological collaboration infrastructure. In addition, the relationship between sustainability's environmental, social and economic components and Industry 5.0 is emphasised [6].

The concept of ESG was first introduced in the United Nations Global Compact [8]. The concept of ESG emerged from the abbreviation of the words "Environmental", "Social" and "Governance". ESG is a process that shows the performance of businesses on issues such as environmental sustainability, employee and community relations, and ethics in the workplace. Asset managers, investors, financial institutions and other stakeholders use ESG scores to make informed decisions, identify risk propensity, and assess a business's status compared to its peers [6].

Combining the technology-driven infrastructure of Industry 5.0 with the conceptual processes of ESG [9], it is important to consider that Industry 5.0 will strengthen ESG reporting [6, 10], a measure of a business's commitment to fulfilling its social responsibilities.

In terms of evaluating the relationship between Industry 5.0 and ESG, Asif et al. [6] examine the application of Industry 5.0 in ESG through the lens of fundamental management theories by providing a conceptual analysis of how Industry 5.0 can be leveraged to improve ESG disclosure effectiveness. Fatemi et al. [11] investigated the impact of ESG activities and their disclosure on business value. Sekaran et al. [9] emphasise the importance of using Industry 5.0 in ESG initiatives to sustain an organisation's supply chain and avoid social, environmental, ethical and other risks. Alkaraan et al. [12] also revealed that ESG practices regulate the relationship between corporate transformation disclosures to Industry 4.0 and financial performance. Kumar et al. [13] argue that ESG compliance and the use of Industry 4.0 technologies act as catalysts for adopting green services. Grabowska et al. [14] stated that the Industry 4.0 process does not provide the desired level of explanation about the status of employees and sustainable production in factories, and it is explained that sustainability and employee-related issues are elaborated in the Industry 5.0 process.

When all these studies are evaluated, it is possible to say that the technological infrastructure of Industry 5.0 and the conceptual collaboration of ESG and its applicability to different sectors have significantly contributed to the literature. However, no study examines the Industry 5.0 process with all the components of the ESG process by expressing the Industry 5.0 process as an equation "Industry 5.0 = Industry 4.0 + Employees and Society + Environment + Resilience of Businesses", and as a result, no study reveals this relationship in a matrix table. In addition, no study reveals how these results are evaluated in the white goods sector. It is considered important to investigate further the relationship between the components of Industry 5.0 and ESG. Therefore, while examining the relationship between Industry 5.0 and ESG, this study provides a detailed examination of other important issues that make Industry 5.0 a whole. Based on these explanations, the study aims to determine the relationship between Industry 5.0 and ESG processes. In addition, it is aimed to reveal how this relationship is evaluated within the scope of Vestel and Arçelik enterprises in the white goods sector within the scope of the BIST Sustainability 25 Index in Türkiye. The study sample is made up of Vestel and Arçelik enterprises. Docu-

Table 1. Industry 5.0 process and its components

INDUSTRY 5.0 [37–40]	Industry 4.0 [40-42]		Environment	Employee and human	Resilience
Data (Formerly known as Big Data) and Knowledge Process (Data Acquisition → Data Storage → Data Analysis → Valuable Knowledge)					
Cyber Security (OT / IT / Employee) [43,45]					
	Vertical integration; Horizontal integration	Technologies	Energy efficiency [62]	Employees [65]	Digital resilience; IT and OT infrastructure resilience [39–41, 51]
	Employees and technology integration; **Customers**: Connected customers and smart products	Operational technologies (OT) [51]; Information technologies (IT) [58]	Sustainable production [63]	Employee and tech. collaboration [53, 64]	Cyber resilience [67, 68]
	OT and IT technologies; **Suppliers and logistics**: Connected suppliers and logistics	Autonomous vehicles [47]; Cobots [52]; Digital twin [53]; Addictive manufacturing [48]; 4-d Printing; **Cloud computing systems** [59]: Public, Private	Sharing economy [64]	An employee is a Value not an Asset [66]	Culture resilience [48–50]
	Department collaboration (human Resources, Finance, etc.); **Government**: - Connected government - Laws and incentives	**IOT** [54]; Sensors; Actuators; Wearable technologies [40]; **Communication technologies** [59, 60]: 5G, Wifi v6, LoRa Wan	Circular economy [63]	Hybrid Int. (AI + human Int.) [66]	Environmental resilience [63, 65]
	Interdisciplinary studies [40, 46]: Bio-tech., Nanotech., Health, Chemical, Other disciplines	A R, VR, XR; NFT [57]; Block chain [56]; Metaverse [55]; Smart products [58]; **Data storage**: Public [59], Cloud [59]	Waste management with tech [65]	Society [39]	Natural disasters resilience [38]
	New business models [40, 47]: PaaS, subscription-based systems (software, asset usage, etc.), metaverse platforms, open innovation platforms, etc.	**OT and IT Software Infrastructure** [51-53, 61]: AI, ERP, BI, MES, RPA, Finance and Human Resources Software, IT Management Software, etc (All of them Connected with others),	Environmental friendly smart products [65]	Economic, healthcare, education, culture, etc. [48, 58]	Other risks res. (epidemic disease, disruptive technological developments, etc) [38]
	Organizational Digital Culture [48, 50]				
CPS (Cyber-Physical Systems) [52, 54]					

Source: Authors Elaboration.

ment analysis was used as the data collection method in the study. For this purpose, document analysis, one of the qualitative analysis techniques, was used to answer the study's first research question (RQ1), " How are the components of the Industry 5.0 and ESG processes related to each other?". In this context, the references in the bibliography section of the study were scanned, and the sub-components of the components of the Industry 5.0 process are shown in Table 1. The components of the ESG process are also shown in Figure 1. Afterwards, the components of Industry 5.0 and ESG processes were placed in a matrix table (Table 2), and their relationship with each other was tried to be explained. In this way, the theoretical dimension of the study emerged. This theoretical dimension also forms the basis for the other research questions of the study. It is thought that the information on Industry 5.0 and ESG processes revealed in both Table 1 and Figure 1 will provide an important reference for researchers who will work in this field.

After presenting the theoretical dimension of the study through document analysis, descriptive content analysis, one of the qualitative analysis techniques, was used to reveal how the relationship between the Industry 5.0 process and the ESG process is evaluated within the scope of Vestel and Arçelik enterprises in the white goods sector within the scope of the BIST Sustainability 25 Index in Türkiye. In this context, the annual reports of Vestel and Arçelik enterprises for 2022 were examined, and the following research questions were asked to be answered.

RQ2. In which areas do Vestel and Arçelik enterprises in the BIST Sustainability 25 index work within the scope of Industry 5.0?

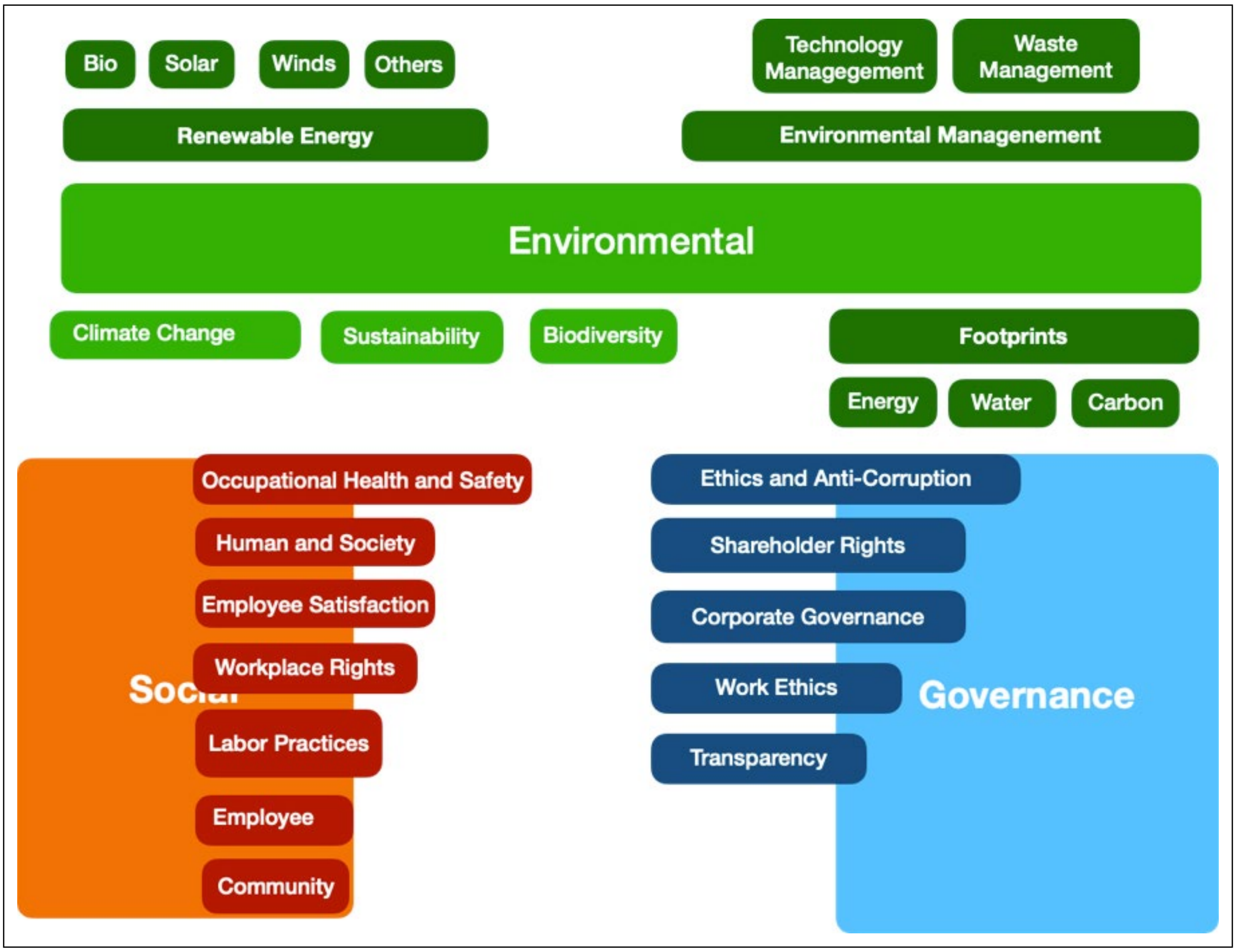

Figure 1. ESG concept and subcomponents (Source: Authors Elaboration).

RQ3. In which areas do Vestel and Arçelik enterprises in the BIST Sustainability 25 index work on ESG process?

RQ4. What is the relationship between the components of Industry 5.0 and the ESG components of environment, social and governance in Vestel and Arçelik enterprises in the BIST Sustainability 25 index?

Research questions 2, 3 and 4 of the study can be considered as the application of the relationships revealed in Research Question 1.

As a result of the study, it was concluded that both enterprises have carried out similar studies on the Industry 5.0 and ESG processes. In both enterprises, the technological infrastructure of the Industry 5.0 process contributes to ESG processes.

Finally, evaluations are made in the conclusion section based on all the findings.

CONCEPTUAL FRAMEWORK

Industry 5.0 Process

The Industry 5.0 process can be defined as a new industrial revolution that is being studied after the Industry 4.0 process. The Industry 5.0 process aims to bring solutions to the human and employee factors and environmental issues not fully explained in the Industry 4.0 process. Industry 5.0 is focused on combining the innovation and labour of human beings with the speed, productivity and adaptability of robots. This collaboration is described as a human-centred approach [1, 15]. In this context, it can be said that the Industry 5.0 process focuses on a sustainable environment and the resilience of businesses against risks through the collaboration of employees, people and technology [16–18].

The rapid rise of artificial intelligence technologies in the Industry 5.0 process has led to the addition of artificial intelligence (AI) to the human-centred approach. The collaboration of artificial intelligence and human intelligence is called hybrid intelligence or hybrid intelligence. Thanks to hybrid intelligence, both a significant increase in interdisciplinary studies and new business models are expected to emerge [5].

Industry 5.0 was named Society 5.0 by the Japanese government. The reason for this naming is that all advanced information technologies, artificial intelligence, augmented reality and robots are aimed to be actively used in the manufacturing industry, supply chain, business management and daily life and thus become an essential factor in ensuring the welfare of society [3, 7].

Table 2. Matrix table of industry 5.0 process and ESG process components

ESG				
Environmental	**Social**	**Governance**		
With technological progress, it is aimed to contribute to environmental problems, and sustainable production infrastructure is being worked on. To establish this infrastructure, businesses must complete vertical and horizontal integration processes [6, 75].	Studies should be carried out on the collaboration of employees and technology. With the development of smart products, the satisfaction of people (society), who are the enterprise's customers, with the products they buy can be increased to higher levels. In addition, product improvements can be made more efficiently with customer data [6, 9].	Technology constitutes the infrastructure for the establishment of the organisational structure in accordance with the digital culture, efficient communication between departments and the elimination of silos, and ethical and traceable relations with stakeholders [6, 48, 49].	**Industry 4.0**	**Industry 5.0**
The focus is on environmental issues such as biodiversity, water, carbon and energy footprints, and climate change. Technological collaboration is essential to address these issues efficiently. However, producing products with high sustainability rates is one of the studies that can be carried out in this field [75, 76].	People's purchase of products with high sustainability rates contributes to environmental sustainability. In addition, the welfare of people is also increased with the technological improvements provided by such products. At the same time, employees should be reminded that technology is valuable as long as it serves the environment and people by providing the necessary environmental sustainability training [6, 75].	Corporate governments must support developments that contribute to environmental sustainability [59]. While making investment decisions regarding the technological infrastructure of developments related to sustainability and calculating the costs in this regard, social contributions should be considered in the cost calculation for issues about environmental problems [9, 73].	**Technology for environment**	
Environmental sustainability, Net 0 target, water and energy footprints, biodiversity, [82] contributing to environmental sustainability as employees and society, and making them more agile thanks to the momentum gained with the help of technological developments should become the goal of businesses, employees and society [9, 26].	The employee should be seen as a value. The machinery and equipment used by the employees ensure that the business processes are carried out efficiently. It is essential to continuously educate employees about technology and environmental problems, human and social relations. Efforts should be made to ensure that technological progress can increase the welfare of employees and people (society) [30, 39]	In return for employees and society, concepts such as ethical values and anti-corruption are emphasised. The transparent implementation of these concepts depends on technological progress and infrastructure. A digital infrastructure ensures that information about the business can be seen more transparently and ethical board human rights violations can be revealed more quickly [9, 29].	**Technology for employee and human (society)**	
There is an essential relationship between resilience and environmental sustainability activities. If every business and society pays attention to individuals' environmental processes, business resilience and society will increase against environmental threats. In addition, trade between businesses that comply with the laws set by the states regarding environmental processes becomes easier. Businesses that do not comply may have problems, especially related to exports. This can lead to significant weaknesses in the resilience of businesses. [9, 22, 71]	It is emphasised that as businesses focus on moral and ethical values, their relations with their stakeholders can be established healthily, and thus, business resilience can be increased. If employees, people (society) and businesses can collaborate on fundamental values, the culture of solidarity is strengthened. In this way, it is possible to work for the welfare of the society [9, 75].	Studies should be conducted to increase Business Resilience against sudden threats such as COVID-19, natural disasters, cyber security, and disruptive digital innovation threats. Corporate management processes should be digitalised to ensure uninterrupted communication between business departments, automation of data acquisition processes related to the work done to eliminate silos between units, artificial intelligence-supported process automation and continuous repetitive workloads on units other than production should be taken [9, 27]	**Resilience**	

The most important difference of Industry 5.0 from other industrial revolutions is that it starts without disruptive technological innovation. Industry 5.0 aims to solve the issues of human-centeredness, sustainability and resilience of businesses in the light of the technological infrastructure of the previous industrial revolution, Industry 4.0 [6]. In this regard, Xu et al. [19] emphasise the value given to people and the environment by considering Industry 4.0 as technology-oriented and Industry 5.0 as value-oriented.

One of the distinguishing features of the Industry 5.0 process is the sustainability approach. In this way, it is expected to minimise the impact of businesses on the environment while producing and to provide maximum benefit from the products produced, including recycling. It is stated that the Industry 5.0

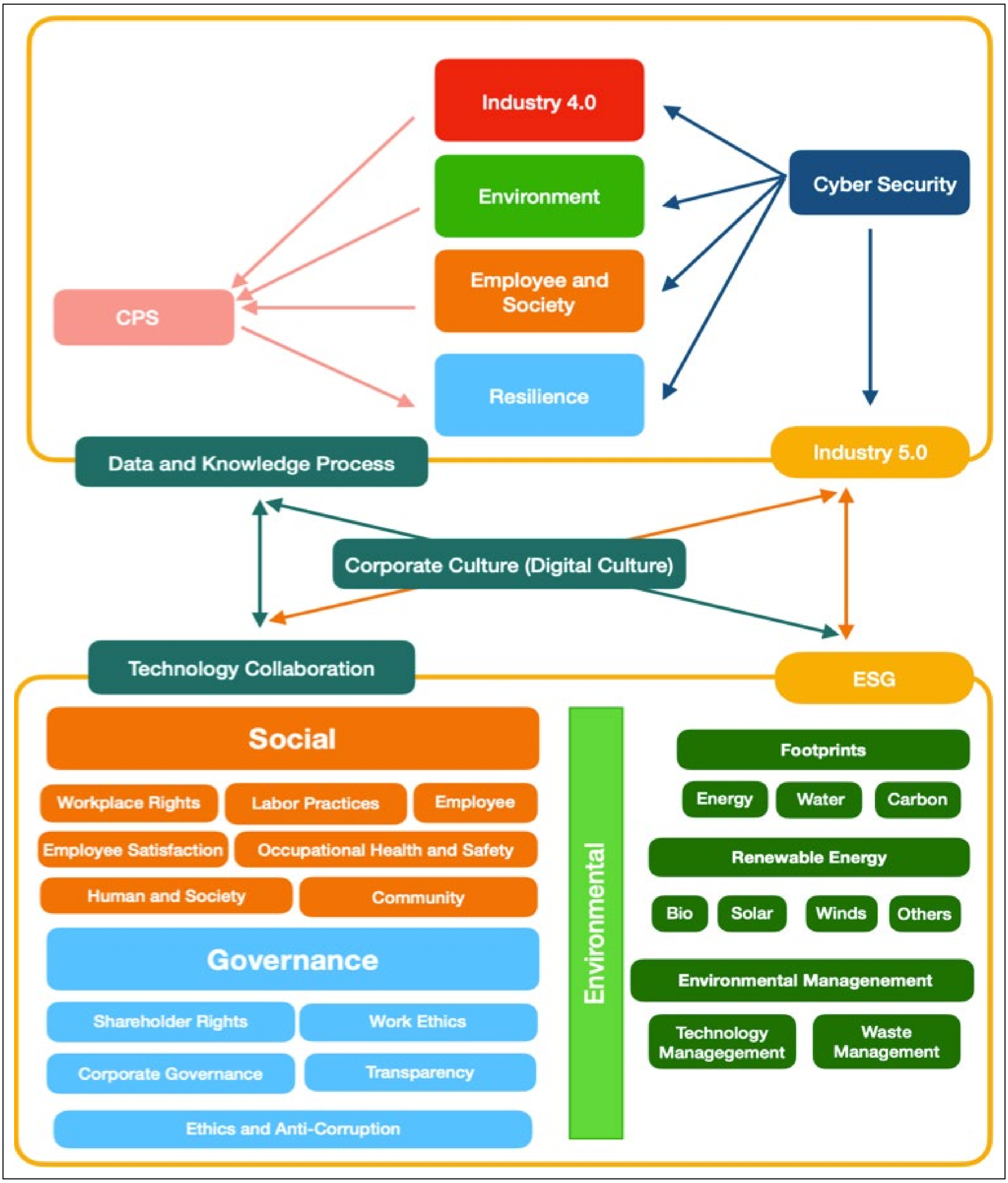

Figure 2. The relationship between Industry 5.0 and ESG process (Source: Authors Elaboration).

process will help establish a sustainable balance between ecology, industry and economy through the intelligent use of biological resources for industrial purposes [3, 18]. Asif et al. [6] state that the concept of Society 5.0 is closely aligned with the Sustainable Development Goals of the United Nations. In order to achieve sustainable development in all areas that concern society (such as education, health and economy), it is essential for society to establish positive relationships with technology [20].

The Industry 5.0 process emphasises the welfare of society and employees, the sustainability of the environment, as well as the resilience of businesses against all kinds of risks and crises. In this context, the efforts made to ensure that production and services do not stop under all kinds of risks and crises and that society and the sector are minimally affected are directly related to the resilience of businesses [19].

As a result of all these explanations, the Industry 5.0 process can be briefly expressed as "Industry 5.0 = Industry 4.0 + Environment + Employees and Society + Resilience of Businesses".

ESG Process

The concept of ESG was explained in detail in a report titled "Who Cares Wins" prepared by the United Nations in 2004 [8, 21]. Before this concept, the sectors to be invested in were determined according to the ethical guidelines determined by the Socially Responsible Investing (SRI) concept. ESG has started to be used as an alternative to SRI in this context [22].

The Environmental component of the ESG process describes the environmental issues and standards of a business and its stakeholders, such as carbon emissions and waste management. The Social component describes social issues and standards, such as employee rights and community issues. The Governance component describes issues and standards such as corporate policies, transparency, and workplace ethics [9]. It is emphasised that the market values of businesses that invest in these standards can positively affect global financial markets [23]. In this context, these standards define non-financial performance indicators of businesses [24]. The resulting ESG score, which maps a business's performance in three dimensions: environmental, social, and governance, is used by investors, buyers, regulators, and other stakeholders [6].

The report generated while preparing the ESG score is based on internal and external data sources [25, 26]. Internal data sources include data from businesses's environmental management systems, quarterly and annual financial, governance and performance reports, corporate leadership reports, executive salary disclosures and press releases. External data sources include news, media reports analysed through natural language processing, and data obtained through social media [6, 27, 28]. Businesses that perform well in the components of ESG can easily adapt to market conditions, and such businesses may gain an advantage in being preferred by investors.

The performance of a business in the components of ESG provides a holistic picture of a country's economic prospects and business environment, which enables businesses to make informed investment decisions in line with the United Nations Sustainable Development Goals [10, 29, 30].

In Türkiye, businesses that can take their ESG efforts to the next level are included in the BIST Sustainability 25 Index. The BIST Sustainability Index emerged for the first time in 2014. As a result of the basic rules published in 2014, 25 enterprises were included in this index. Within these rules, the sustainability performance of the enterprises to be included in this index, other than their financial performance, was evaluated by the Ethical Investment Research Services Limited (EIRIS) Organization [27]. These evaluation criteria include environmental, governance and social areas. In 2021, the London Stock Exchange Group (LSEG) was selected as the criteria evaluator [28]. The selection criteria were taken from ESG work areas [29, 30].

Relationship Between Industry 5.0 and ESG Processes

In 2004, it was seen that the ESG components in the report prepared by the United Nations and the components of the Industry 5.0 process are parallel. In this report, it is thought that businesses with better ESG performance can better manage environmental, social and governance risks and take necessary measures [6, 31]. They are also assumed to predict consumer trends more accurately [6, 32]. The collaboration of the employee, society, and environment components described in the Industry 5.0 process through the technology component emphasises the environmental, social, and governance components of the ESG process. However, it is thought that there is a bidirectional relationship between the content of the ESG process and the content of the Industry 5.0 process. This statement is supported by Asif et al. [6] and Kumar et al. [13] in the literature. In other words, investing in the ESG process also means moving forward in the Industry 5.0 process, and investing in the Industry 5.0 process also means moving forward in the ESG process.

Studies on Industry 5.0 and ESG processes are generally discussed in international environments and enter the literature. Considering the general and corporate culture when implementing these processes for businesses in Türkiye or any other country is essential. Because culture may have different sub-components for each nation. Since corporate culture is also affected by general culture, it would be appropriate for businesses to pay attention to cultural issues [33].

The following research question was put forward to reveal the dimensions of the relationship between Industry 5.0 and ESG processes.

RQ1. How are the components of the Industry 5.0 and ESG processes related? In line with the first research question, the following questions were posed to reveal how the theoretical relationship between Industry 5.0 and ESG processes is evaluated from Vestel and Arçelik enterprises in the white goods sector included in Türkiye's BIST Sustainability 25 index.

RQ2. In which areas do Vestel and Arçelik enterprises in the BIST Sustainability 25 index work within the scope of Industry 5.0?

RQ3. In which areas do Vestel and Arçelik enterprises in the BIST Sustainability 25 index work on ESG process?

RQ4. What is the relationship between the components of Industry 5.0 and the ESG components of environment, social and governance in Vestel and Arçelik enterprises in the BIST Sustainability 25 index?

MATERIALS AND METHODS

This study aims to determine the relationship between Industry 5.0 and ESG processes. In addition, this study aims to reveal how this relationship is evaluated within the scope of Vestel and Arçelik enterprises in the white goods sector within the scope of the BIST Sustainability 25 Index in Türkiye.

For this purpose, to determine the relationship between Industry 5.0 and ESG processes, document analysis, one of the qualitative analysis techniques, was used within the scope of the first research question and the references in the bibliography section of the study were reviewed. Document analysis can be used as a stand-alone analysis, or it can be used to support other analysis techniques [34]. This study used document analysis to determine the relationship between Industry 5.0 and ESG processes. In addition, it was also used to support descriptive content analysis to reveal how the relationship between Industry 5.0 and ESG processes is evaluated in Vestel and Arçelik. The sub-components of the components of the Industry 5.0 process are shown in Table 1. The components of the ESG process are also shown in Figure 1. Afterwards, a matrix table was generated to show the relationship between all components of Industry 5.0 and ESG processes. Each of the intersections of the rows and columns of the table shows the relationship of the components in the row and column.

Descriptive content analysis, one of the qualitative analysis techniques, was used to reveal how the relationship between the Industry 5.0 process and the ESG process is evaluated within the scope of Vestel and Arçelik enterprises in the white goods sector within the scope of the BIST Sustainability 25 Index in Türkiye. Descriptive analysis is the presentation of the data obtained from interviews, observations and document analysis to the reader in an organised and interpreted manner [35]. Descriptive content analysis requires examining the collected data in more detail and identifying the concepts, categories, and themes that explain these data [36]. In this context, the annual reports of Vestel and Arçelik for the year 2022 were analysed to answer research questions 2, 3 and 4. The answers to the research questions were tried to be revealed as a result of the analysis of the statements used by Vestel and Arçelik enterprises in their annual reports in the Nvivo program.

Only Vestel and Arçelik, which are included in the BIST Sustainability 25 Index and meet the relevant criteria from the white goods sector, were selected as the study sample by convenience sampling method.

Document analysis was preferred as the data collection method in the study. In this context, the annual reports of the enterprises and all references mentioned in the bibliography section were analysed. While examining the annual reports, the analysis was carried out in accordance with the equation "Industry 5.0 = Industry 4.0 + Environment + Employees and Society + Resilience of Businesses" and the components of the ESG process. In the NVivo (version 14.23.2) program, a code configuration parallel to Table 1 and Figure 1 was made. For each code, the statements used in the annual reports were scanned.

During the descriptive content analysis in the study, it was observed that information on the concept of ESG was clearly stated in the annual reports. However, no explicit statement about the Industry 5.0 process was found. For this reason, during the analysis, an appropriate coding was made on the right side of the equation: "Industry 5.0 = Industry 4.0 + Environment + Employees and Society + Resilience of Businesses". The value provided by the results of this coding to the main statement on the left side of the equation was revealed.

FINDINGS AND EVALUATIONS

RQ1. How are the components of the Industry 5.0 and ESG processes related?

The components of the Industry 5.0 process are Industry 4.0, environment, employees and society, and resilience of businesses. In the study by Grabowska et al. [14], the Industry 5.0 process was examined as human-centeredness, sustainability and resilience of businesses, similar to the component structure in this study. In order to facilitate the examination of the components within the scope of document analysis and to reveal the Industry 5.0 process in all its details, the Industry 5.0 process is expressed as an equation as follows.

"Industry 5.0 = Industry 4.0 + Environment + Employees and Society + Resilience of Businesses".

The most important reason for expressing the components of the Industry 5.0 process as an equation is to reach the expression on the left side through studies on the components on the right side. In this way, even if a business does not refer to the Industry 5.0 process in its studies, it is thought to structure the Industry 5.0 process with the studies on the components on the right side. In this context, Table 1, which presents the Industry 5.0 process obtained from the literature scanned by document analysis, was generated. In accordance with the equation expressed in the study, Table 1 shows the Industry 5.0 process in 4 subcategories: Industry 4.0, employee and society, environment and resilience of businesses.

The abbreviation list of Table 1 is as follows:

NFT (Non-fungible Token), OT (Operational Technologies), IT (Information Technologies), PAAS (Product as a Service), AR (Augmented Reality), VR (Virtual Reality), XR (Extended Reality), AI (Artificial Intelligence), ERP (Enterprise Resource Planning), MES (Manufacturing Executing System), BI (Business Intelligence), RPA (Robotic Process Automation), Env. (Environment), Res. (Resilience), Tech. (Technology), Int. (Intelligence)

Similar to the Industry 5.0 process, the components of the ESG process were analysed in 3 different subcategories as a result of the document analysis. As a result of this analysis, Figure 1 was drawn, and the sub-components of the components of the ESG process were also shown.

It is understood that the environmental component of the Industry 5.0 process constitutes the technological infrastructure of the issues within the scope of the environmental component of the ESG process. The study by Asif et al. [6] also supports that the environmental components of these two processes are interrelated. While the social component of the ESG process focuses on employee, stakeholder and

Table 3. Evaluation of the activities carried out by Vestel and Arçelik about Industry 4.0 component within the scope of the Industry 5.0 process through their annual reports

Industry 4.0	Vestel	Arçelik
	94	91
New business models	6	1
Digital culture	6	2
Data and knowledge process	12	9
Cyber security	11	5
CPS	1	1
Vertical and horizontal integration (collaboration)	62	73
Vertical integration	41	39
Departments	1	2
Technologies	40	37
Operational technologies	23	17
AR	2	1
VR	1	1
NFT	0	1
IOT	14	6
Digital twin	1	5
Cobots	2	1
Addictive manufacturing	2	1
Others	1	1
OT software infrastructure	10	8
AI	3	5
BI	0	1
Others	7	2
Information technologies	6	8
Data storage	0	0
Local	0	0
Cloud	0	0
Cloud computing systems	3	3
Public clouds	2	1
Private clouds	1	2
Communication technologies	0	1
IT software infrastructure	1	4
RPA	1	4
Horizontal integration	21	34
Suppliers	10	12
Logistics	2	7
Government	0	0
Customers	9	15

community relations, the employee and community component of the Industry 5.0 process ensures that this focus can be maintained more efficiently through technological collaboration [69, 70]. For example, horizontal integration may ensure more efficient communication between businesses and their customers and suppliers and thus establish a fair commercial structure [5, 54, 71]. The relationship between the resilience of the businesses component of the Industry 5.0 process and the governance component of the ESG process is also focused on technological infrastructure and collaboration. For example, for the relevant enterprise to be monitored and audited transparently by stakeholders and to prevent corruption, every process should be recorded. These records should not be changed; even if they are changed, it should be known by whom, when and for what reason. In addition, ensuring communication within the organisation and eliminating silos between business departments is also through technology-oriented communication [72, 73]. This relationship is confirmed by studies in the literature [6, 26, 74].

Table 4. Evaluation of the activities carried out by Vestel and Arçelik about the environmental component within the scope of the Industry 5.0 process through their annual reports

Environment (with technology collaboration)	Vestel	Arçelik
	31	25
Technology for the environment	3	2
Sustainable production	9	9
Sharing economy with technology	0	0
Energy efficiency	8	9
Circular economy	11	5

The relationship between Industry 5.0 and ESG processes can be expressed in Figure 2 by utilising Table 2 and the knowledge revealed from the document analysis.

RQ2. In which areas do Vestel and Arçelik enterprises in the BIST Sustainability 25 index work within the scope of Industry 5.0?

No terminology related to Industry 5.0 was found in the annual reports of either Vestel or Arçelik. In accordance with the methodology of the study analysis, an attempt was made to identify the "Industry 5.0" process on the left side of the equation derived from "Industry 4.0 + Environment + Employees and Society + Resilience of businesses" on the right side. Tables 3, 4, 5 and 6 show the structure that emerged in this context. In this context, it is seen that both enterprises carry out studies on the Industry 5.0 process, although they do not explicitly use the term "Industry 5.0". The findings obtained from the examination made by considering all the components in the equation one by one are given below, respectively.

i. Industry 4.0: Table 3 presents the data obtained from analysing the annual reports of Vestel and Arçelik with the help of NVivo software in relation to the activities carried out by these enterprises within the scope of Industry 4.0 technology. On the left side of this table, the technologies and processes found in the annual reports, in accordance with Table 1, are written. On the right side of the table, the extent

Table 5. Evaluation of the activities carried out by Vestel and Arçelik about employees and society components within the scope of the Industry 5.0 process through their annual reports

Employee and society	Vestel	Arçelik
	17	17
Technology for human	7	8
Hybrid intelligence	0	0
Employee is a value, not an asset	1	3
Employee and technology collaboration	9	6

Table 6. Evaluation of the activities carried out by Vestel and Arçelik about the resilience of businesses within the scope of the Industry 5.0 process through their annual reports

Resilience	Vestel	Arçelik
	13	10
Environmental resilience	3	3
Digital resilience	5	2
Cyber resilience	5	5

to which these technologies and processes are mentioned in the annual reports of Vestel and Arçelik and the activities carried out are shown.

When evaluated in terms of Industry 4.0 components within the scope of Industry 5.0, it can be seen that Vestel (94) has more statements regarding Industry 4.0 technology than Arçelik (91) in the annual reports of Vestel and Arçelik. When analysed in detail, it is seen in Table 2 that the statements related to horizontal and vertical integration are the most frequently used statements in the annual report in terms of Industry 4.0 components. When horizontal and vertical integration is considered, it is understood that Arçelik, with 73 statements, included more statements in its annual report compared to Vestel's annual report. When horizontal integration and vertical integration are considered separately, it is seen that Vestel (41) included more statements in its annual report than Arçelik (39) in horizontal integration, while Arçelik (34) included more statements in its annual report than Vestel (21) in vertical integration. Apart from these, it is observed that Vestel has more statements related to new business models, digital culture, data and knowledge process, cyber security, operational technologies - especially IOT technology, and OT software infrastructure codes than Arçelik. Table 2 shows that Arçelik has more statements related to information technologies and IT software infrastructure than Vestel.

It is seen in Table 2 that both enterprises are working intensively on the Industry 4.0 process. The studies conducted are similar to each other. Vestel's annual report provides more information on cyber security, digital corporate culture and new business models, while Arçelik's annual report provides more information on digital twin and RPA technologies.

It was found that Arçelik included more information on horizontal integration processes in its annual report than Vestel. Vestel, on the other hand, gives more importance to vertical integration processes than horizontal integration.

Both enterprises' annual reports found insufficient information on Metaverse, NFT, and blockchain infrastructure. It is thought that the importance of these technologies will increase more in the future. Thanks to the widespread use of 5G fast mobile internet infrastructure, metaverse infrastructure systems may develop further.

It may be very important for the stakeholders of the enterprises in the current study to focus relatively more on their activities related to Industry 4.0 in their annual reports and to clarify the efforts they have made and will make in this field.

ii. Environment: The evaluation of Vestel and Arçelik's activities related to the environment within the scope of the Industry 5.0 process through their annual reports is given in Table 4.

When Table 4 is analysed, it is determined that Vestel (31) uses more environmental statements than Arçelik (25).

It is seen that both enterprises use technology for sustainable production and a more livable environment within the scope of the Industry 5.0 process. Both enterprises included sustainable production in their annual reports equally. Circular economy issues are covered more in Vestel's annual report than in Arçelik's. Both enterprises work intensively on energy efficiency. These efforts are thought to be related to the environmental component of the ESG process [7]. Environmental issues are made more sustainable through technology collaboration. In this way, contributions are made to the ESG process.

iii. Employees and Society: The evaluation of Vestel and Arçelik's activities related to employees within the scope of the Industry 5.0 process through their annual reports are presented in Table 5.

When Table 5 is analysed, it is seen that both enterprises have conducted studies on the use of technology in collaboration with employees and society. While Vestel's annual report contains more explanations and studies on the collaboration between technology and employees, Arçelik's annual report contains more explanations and studies on the value of employees.

Table 7. Evaluation of Vestel and Arçelik's annual reports regarding the Industry 5.0 process

	Industry 5.0	=	Industry 4.0	+	Environment	+	Employee and society	+	Resilience
Vestel	155		94		31		17		13
Arçelik	143		91		25		17		10

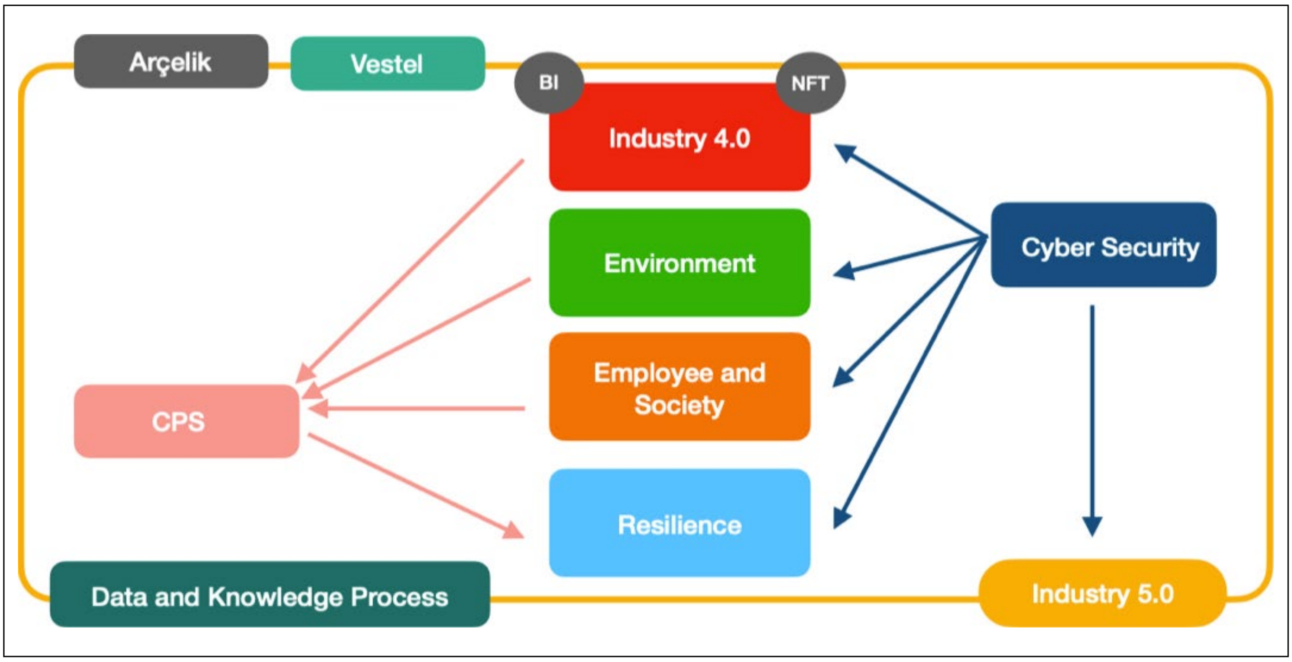

Figure 3. Comparison of Industry 5.0 process components through Arçelik and Vestel annual reports (Source: Authors Elaboration).

Both enterprises declared in their annual reports that they develop and use technology to benefit society and explained their efforts in this area. The effects on the social component of the ESG process are strengthened with the expansion of technology and employee collaboration in the Industry 5.0 process to society [6].

iv. Resilience of Businesses: The evaluation of Vestel and Arçelik enterprises' activities related to the resilience of businesses within the scope of the Industry 5.0 process through their annual reports is given in Table 6.

When Table 6 is analysed, it is seen that both enterprises conduct studies on resilience. Resilience studies on cyber security are equally included in the annual reports of both enterprises. There are more studies on digital resilience at Vestel (5) than at Arçelik (2). Digital resilience not only increases resilience against threats such as pandemics and natural disasters, but it is also important for solving problems such as solving communication problems within the organisation, removing silos between business units, making production processes more efficient, and not being able to evaluate employee performance fully [75, 76]. These studies are considered to be related to the governance component in the ESG process and are supported by studies in the literature [9, 77, 78].

When evaluated for the concepts considered as components of Industry 5.0 and expressed as equations in the study, the statements included in the annual reports of both enterprises are given in Table 7.

When Table 7 is analysed, it is seen that Vestel's annual report includes a total of 155 statements regarding the Industry 5.0 process, while Arçelik includes 143 statements. When Table 7 is analysed, it is seen that both enterprises are engaged in intensive activities related to the components on the right side of the equation.

As a result of the evaluation of Tables 3, 4, 5 and 6 together, the findings showing the comparison of Vestel and Arçelik enterprises' activities related to the Industry 5.0 process according to their annual reports are presented in Figure 3.

RQ3. In which areas do Vestel and Arçelik enterprises in the BIST Sustainability 25 index work on ESG process?

The studies conducted for the ESG process have similar characteristics for both enterprises. In this regard, it has been determined that both enterprises focus on sustainability, ethics, workplace rights, and social issues and carry out studies. These studies are necessary to be included in the BIST Sustainability 25 index. The findings from the environmental, social, and governance components of the ESG process are given below.

i. Environment (E): The evaluation of Vestel and Arçelik on the environmental component of the ESG process through their annual reports is presented in Table 8.

Table 8 shows that Vestel includes more environmental issues in its annual reports compared to Arçelik. Noteworthy results reveal that Vestel uses more statements on sustainability, waste management, footprint, water and energy than Arçelik. On the other hand, only technology management and climate change are more frequently mentioned in Arçelik than in Vestel.

ii. Social (S): The evaluation of Vestel and Arçelik's activities related to the social component of the ESG process through their annual reports is presented in Table 9.

Table 9 shows that Arçelik includes more social issues in its annual reports compared to Vestel. Arçelik uses more statements on shareholder rights, occupational health and safety and employee satisfaction than Vestel.

Table 8. Evaluation of the activities carried out by Vestel and Arçelik about the environmental component of the ESG process through their annual reports

Environment	Vestel	Arçelik
	124	77
Sustainability (resource efficiency)	24	17
Renewable energy (solar)	5	5
Waste management	34	8
Technology management	1	3
Climate change	14	17
Biodiversity	6	6
Footprints	31	24
Water	10	7
Energy	9	3
Carbon (net 0)	14	14

iii. Governance (G): The evaluation of Vestel and Arçelik's activities related to the governance component of the ESG process through their annual reports is presented in Table 10.

Table 10 shows that Arçelik includes more governance issues in its annual reports than Vestel. It is noteworthy that Arçelik has more statements on corporate governance than Vestel, and Vestel has more statements on ethics and anti-corruption than Arçelik.

When the studies conducted by Vestel and Arçelik, both of which are included in the BIST Sustainability 25 index, on the ESG process are analysed, the fact that both enterprises show similarities in ESG-related issues can be attributed to their inclusion in the BIST Sustainability 25 index. In order to be included in this index, studies on ESG issues are required.

As a result of the evaluation of Tables 8, 9 and 10 together, the findings showing the comparison of Vestel and Arçelik's ESG-related activities according to their annual reports are presented in Figure 4.

RQ4. What is the relationship between the components of Industry 5.0 and the ESG components of environment, social and governance in Vestel and Arçelik enterprises in the BIST Sustainability 25 index?

Within the scope of Industry 5.0 and ESG processes, the findings obtained based on examining the studies conducted by Vestel and Arçelik enterprises were evaluated. According to this evaluation, the relationship between the Industry 5.0 process and the ESG process was revealed by comparing the statements used in the annual reports of Vestel and Arçelik, which are included in the BIST Sustainability 25 index, within the scope of the components of these processes.

When the annual reports of Vestel and Arçelik are analysed, it is understood that the activities carried out within the scope of the ESG process are carried out in collaboration with technology [79, 80]. It is observed that both

Table 9. Evaluation of the activities carried out by Vestel and Arçelik about the social component of the ESG process through their annual reports

Social	Vestel	Arçelik
	51	62
Workplace rights	3	3
Shareholder rights	8	15
Occupational health and safety	4	8
Employee and rights	4	3
Human and society	17	14
Employee satisfaction	12	17
Community relations	3	2

Table 10. Evaluation of the activities carried out by Vestel and Arçelik about the governance component within the scope of Industry 5.0 through their activity reports

Governance	Vestel	Arçelik
	37	44
Work ethic	11	12
Transparency	4	5
Shareholders	10	10
Ethics and anti-corruption	5	2
Corruption and bribery	3	5
Corporate governance	4	10

enterprises exhibit some weaknesses in the "People and Workers" section, which is a vital component of the Industry 5.0 process. This assessment is based on the information summarised in the annual report. It is important to note that the Industry 5.0 process shapes the collaboration between employees, society and the environment through technological developments, whereas Industry 4.0 does not share such a focus. At the outset of this study, it is imperative to outline how the collaboration between staff and technology should be formalised through written documentation. This is because the current technologies used can only be sustained with the support of effective staff-technology collaboration. However, it is crucial to determine how to collaborate with AI when AI procedures increasingly dominate business structures. Businesses may benefit from examining hyperintelligence (hybrid intelligence) issues, demonstrating how artificial and human intelligence coexist.

Figure 5 shows the relationship between Industry 5.0 and ESG processes according to Vestel and Arçelik's annual reports.

CONCLUSION

Businesses that try to survive by struggling against uncertainties in the process of rapid change and an environment of intense competition are also dealing with

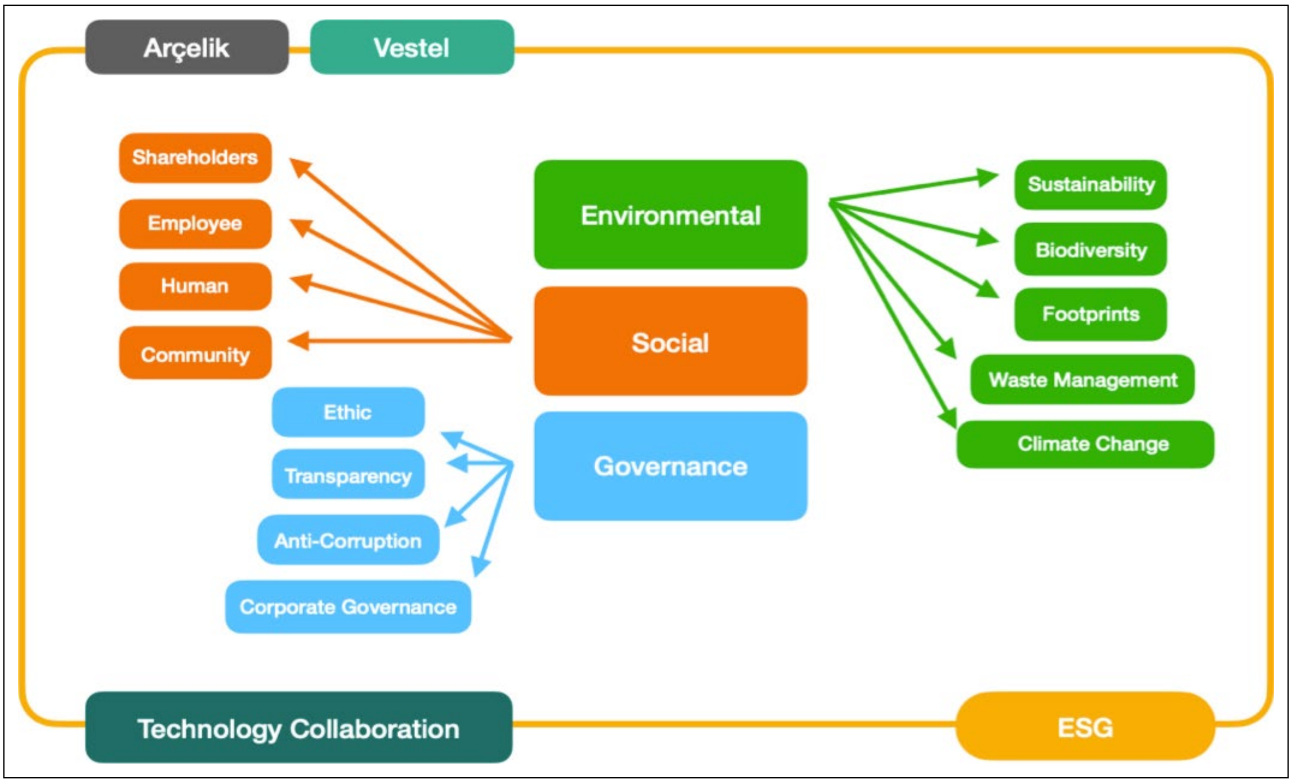

Figure 4. Comparison of ESG process components through Arçelik and Vestel annual reports (Source: Authors Elaboration).

problems such as the threat of deterioration of the world's ecological balance. In this struggle, sustainability principles have been placed on the agenda of profit-seeking organisations depending on the field in which studies are carried out on this threat's environmental, social and economic effects. Businesses now act with great responsibility towards society for a more livable world in the environmental, social and economic fields within the framework of sustainability principles. On the other hand, they produce strategies to survive in an intensely competitive environment. Especially in recent times, with the rapid change experienced within the scope of digitalisation, it develops its strategies depending on the principles of sustainability that can be acted in harmony. Within the framework of these harmonious and socially beneficial activities, it is important for businesses to continue their work in line with the principles of technology and sustainability, both for themselves and for the local community and the world.

The most important distinguishing feature of the Industry 5.0 concept from previous industrial revolutions is the adoption of technological developments in Industry 4.0. This shows that businesses that can complete Industry 4.0 processes can also be successful in the Industry 5.0 process if they address issues related to employees, environment and organisational flexibility.

In this study, to theoretically determine the relationship between Industry 5.0 and ESG processes, the position of employees in the Industry 5.0 process, their compliance and necessity within the sustainability and social benefit principles framework are tried to be revealed in the context of technological collaboration. The annual reports of Vestel and Arçelik, which are in the white goods sector within the scope of the BIST Sustainability 25 Index, were analysed to reveal how the study's theoretical background was evaluated. The Industry 5.0 process is evaluated as a component of Industry 4.0, which includes the environment, employees, society, and the resilience of businesses. These components were formulated using the equation: “Industry 5.0 = Industry 4.0 + Environment + Employees and Society + Resilience of Businesses”. Table 1 was generated in this context, and the Industry 5.0 process was tried to be expressed with all its subcomponents. All subcomponents of the ESG process are also tried to be expressed in Figure 1. By evaluating Table 1 and Figure 1 together, the relationship between Industry 5.0 and ESG processes is shown in the matrix table in Table 2. Each intersection of the rows and columns of Table 2 shows the relationship of the components in the row and column. This relationship constitutes the answer to the employee's research question 1 and the study's theoretical background.

In order to determine how the theoretical background of the study is evaluated by Vestel and Arçelik, the leading representatives of the Turkish white goods industry operating within the scope of the BIST Sustainability 25 Index, the most recent annual reports of both enterprises for the year 2022 were analysed. In this context, it is noteworthy that both enterprises carry out studies with parallel themes. In particular, both enterprises produced studies on Industry 5.0 and ESG processes, which share similar interrelated processes, as shown in Figure 5.

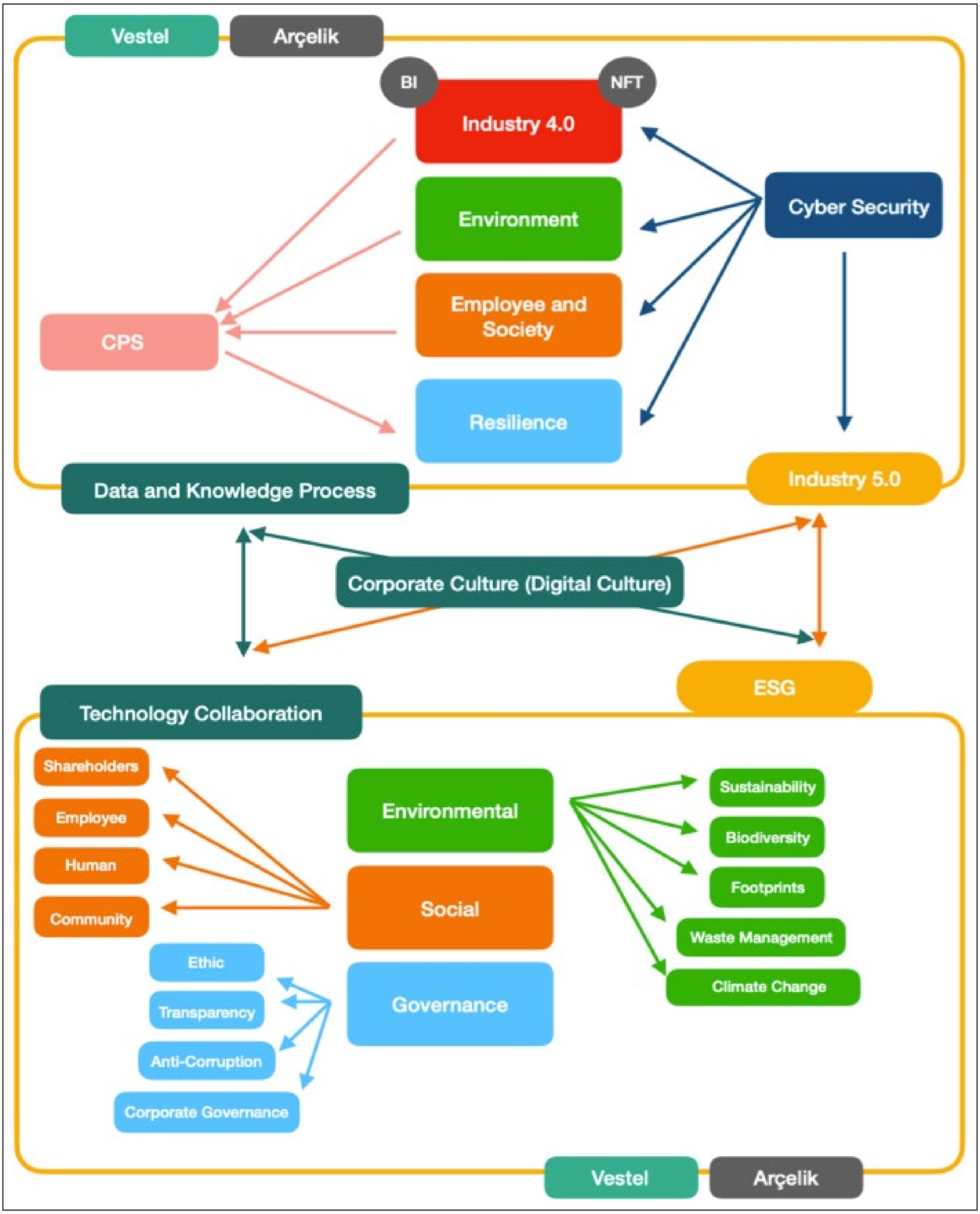

Figure 5. The relationship between Industry 5.0 and ESG processes that emerged as a result of analysing the annual reports of Vestel and Arçelik (Source: Authors Elaboration).

It is recognised that there is an effective correlation between Industry 5.0 and ESG processes. This correlation can be explained by the statement that the Industry 5.0 process forms the technological foundations of the ESG process. The relationship between the concepts related to the environmental component in the Industry 5.0 process within the scope of environment-technology collaboration is closely related to the environmental component in the ESG process. Similarly, the relationship of the concepts related to the employees and society component in the Industry 5.0 process within the scope of employee-society-technology collaboration can be evaluated in the context of generating the technological infrastructure of social concepts in the ESG process. The relationship between the concepts related to the resilience component of businesses in the Industry 5.0 process within the scope of business resilience-technology collaboration is closely related to the governance component in the ESG process. In this context, the technological infrastructure in the Industry 5.0 process minimises the risk of silos in businesses by eliminating communication problems between departments in businesses. Thus, ensuring that the studies on the Industry 5.0 process are more efficient can also contribute to the studies on the ESG process.

This study is intended to help researchers, who study Industry 5.0 and ESG processes theoretically and practically. In addition, it can contribute to developing practices for the ESG process by adapting businesses to technological change. In addition, this study reveals the direction of the relationship between Industry 5.0 and ESG processes. In order to reveal the degree of the relationship, more comprehensive analyses with quantitative or mixed designs should be conducted in different sectors of businesses working on these two processes. However, Tables 1, Figure 1, and 2 presented within the study's scope are valuable as they can guide researchers in creating the infrastructure for quantitative or mixed design studies.

In the application part of this study, the annual reports of two enterprises were analysed. Conducting the study only through the annual report is considered an important limitation. The fact that only two enterprises in the white goods sector are included in the BIST Sustainability 25 Index is considered another limitation.

As a result, it can be stated that one way to expand the implementation of sustainable policies all over the world is for businesses to manage the ESG process well. Those who can adapt their businesses to the Industry 5.0 process that supports sustainable actions can carry out the ESG process more easily.

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.

USE OF AI FOR WRITING ASSISTANCE

Not declared.

ETHICS

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

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Research Article

A novel compatibilizer obtained from olive pomace oil maleate (OPOMA) and evaluation in PLA composite production

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ABSTRACT

Alternative of using organic and biomass residues as additives or reinforcements in the production of composite materials has attracted great attention since the 2000s. However, when lignocellulosic biomass is used as natural fiber in composite production, it may have some disadvantages such as low interfacial bonding with the matrix phase. The most common methods used to strengthen the bonding between the matrix phase and the additive material is to use maleic anhydride (MA) as a compatibilizer and some chemicals such as dicumyl peroxide (DCP) as reaction initiators to increase the compatibilizing effect of MA. Therefore, in this study, olive pomace oil maleate (OPOMA) was prepared to be used in the production of polylactic acid (PLA) composites. Olive pomace obtained with ionic liquid pretreatment (OP-IL) in the previous studies of the authors and OPOMA were used in composite production with a biodegradable polymer of PLA. The composite was obtained by mixing 95PLA+5OP-IL by weight in twin-screw extruder at 190 °C for 10 minutes. Under the same conditions, the effect of OPOMA was evaluated by adding 0.5%, 1% and 2% ratio to PLA + OP-IL. In FTIR spectrum of OPOMA, a new symmetrical and asymmetric C=O bands were formed differently from olive oil. While the tensile strength of the PLA+OP mixture was approximately 10 MPa; the tensile strength value of PLA+OP-IL and PLA+OP-IL+OPOMA was around 60 MPa. The elasticity modulus showed less change compared to other mechanical properties. To conclude, it can be emphasized that oil maleates of lignocellulosic biomasses can be promising compatibilizer for biodegradable composite matrices.

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INTRODUCTION

Composite materials are formed by mixing two or more materials at the macroscopic level to obtain desirable combination of properties [1]. Mostly two or more distinct phases, namely matrix and reinforcing phases, are used during composite material production. Additionally, a phase called as interfacial phase is formed by creating a bond between matrix and reinforcing phases during the composite production and composite strength is highly depended on interfacial bond as it transmits the force to the reinforcement phase without breaking [2–4]. Composite materials are considered more advantageous compared to known traditional materials. The reasons for this can be listed as the fact that the final product material is versatile in terms of structural design and its unique properties such as high specific strength, hardness, and fatigue.

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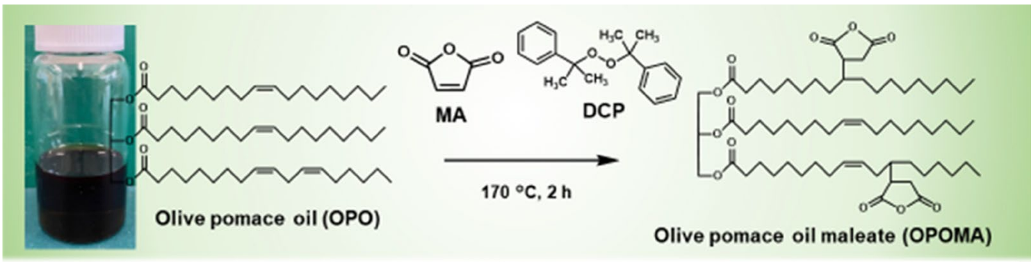

Figure 1. Preparation of olive pomace oil maleate (OPOMA) to apply as compatibilizer (MA: maleic anhydrite; DCP: dicumyl peroxide).

Nowadays, more sustainable approaches needed for producing composites and to this purpose, use of waste materials as additives, environmentally friendly and low-cost solutions become popular. Within environmental friendliness context, this study considered both as biodegradable material and as modifying the waste as next generation raw material to prevent it to be landfilled. In this regard, in many studies, biodegradable plastics (such as polylactic acid (PLA)) are frequently used as matrix in composite production [5, 6]. PLA is a biodegradable polymer can effectively be used for various applications, such as packaging and consumer foods, by virtue of its compostable property, having nontoxic and acceptable mechanical performance. Despite its high price, low thermal stability, brittleness, and crystallinity, which are limiting their applications, PLA is still widely preferred material and improvement of its mechanical properties are still being studied [5–7]. Researchers have been studying some toughening modification methods, such as addition of PBAT, silane and PET-RAN-PLA, however these decrease the biodegradability of the PLA [8]. Therefore, using waste and environmentally friendly materials as reinforcement and filling material while improving and/or keeping the mechanical properties of PLA is critical for maintaining environmentally friendly feature of PLA [6, 8]. However, there are limited studies in the literature about PLA composite material production with environmentally friendly additive materials to enhance and/or change PLA characteristic properties comparing to stated toughening modification methods. Sogut and Seydim [7] studied the effects of kiwi fruit peels (KFP) on the PLA composites, and they emphasized that tensile strength and elastic modulus increased with addition of KFP comparing to PLA control composites. In another study, oat husk and Miscanthus were used as additive materials in PLA matrix composites, and it was emphasized that the additive materials increased the thermal bending temperature, hardness, and strength of the composite material by providing strong interfacial bonding. Moreover, the addition of Miscanthus reduced the water absorption of the polymer matrix [9]. However, the most critical and difficult parts for composites where waste/environmentally friendly materials are used as additive material is to strengthen the interface bonding between the matrix phase and the reinforcement phase. The strength of these bonds affects the mechanical strength of the composites. One of the methods frequently used in the literature to strengthen the bonds between biofiber and PLA is the usage of maleic anhydride (MA)-based compatibilizing agents [10–12]. González-López et al. [13] stated that interfacial adhesion between agave lignocellulosic fiber additive material and PLA composites successfully enhanced with MA addition and 68% increment was obtained in tensile strength of the composite by virtue of MA. Some researchers also use MA and some chemicals such as dicumyl peroxide (DCP) as reaction initiators to increase the compatibilizing effect of MA and matrix phase-additive material bonding. Kiangkitiwan and Srikulkit [14] synthesized soybean oil maleate (SOMA) by reacting soybean oil with maleic anhydride (MA) using dicumyl peroxide (DCP) as the initiator and used the resulting maleate in the production of composites.

These literature findings indicated that biomaterial can successfully be evaluated as additive or functional material in PLA composite mixture. Considering environmental sustainability and carbon footprint, the more valuable solution is to use the waste biomaterial from the closer region. From this point of view, for example, kiwi, or mischanthus, stated above, may not be found in some regions where olive is one of the main agricultural products. Olive (Olea europea) is one of the important food products cultivated for both table olives and oil. Majority of global olive production is in the Mediterranean region, and then in minor quantity in some parts of America and Australia. In olive oil extraction significant amounts of solid and liquid residues become a challenge issue for the olive mill operators from both economic and environmental perspectives. This solid residue is a promising biomass resource because their characteristics provide the opportunity for their potential utilization. In the management of olive pomace new alternative recovery/recycle approaches have been developed for years. Considering the high quantity of yearly residue and well-known valuable properties of the material, alternative evaluation methods have always been studied. Therefore, in this study, olive pomace oil maleate (OPOMA) was produced with a similar approach and tried in PLA: Pretreated Olive Pomace composites as a novel compatibilizer to make contribution of investigation PLA composite material production with environmentally friendly additive materials. Characteristics of OPOMA and mechanical properties of composites were also investigated.

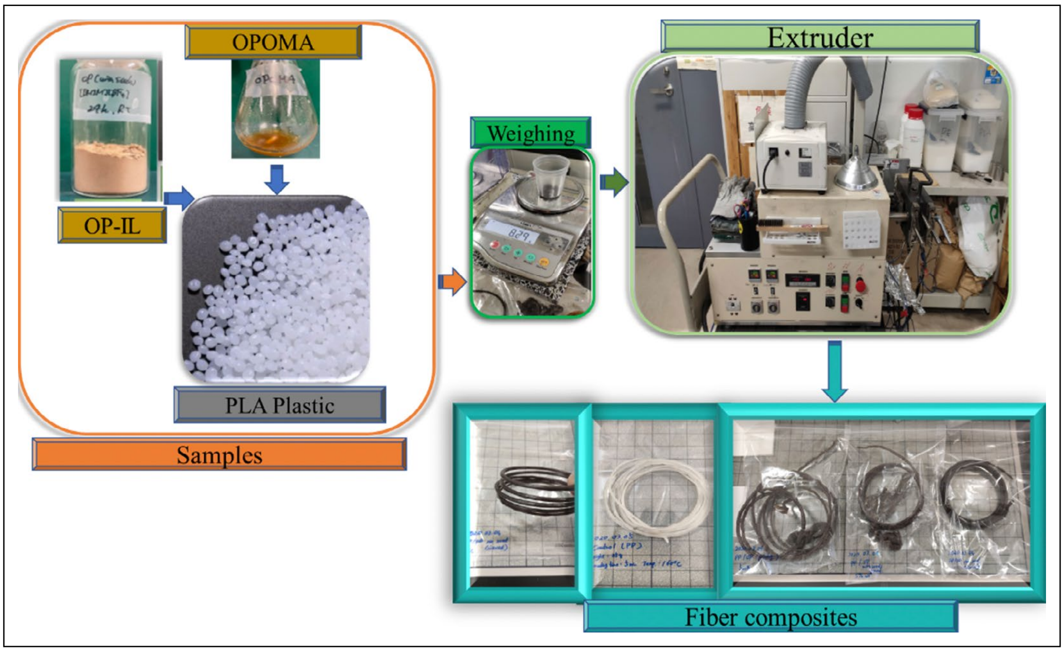

Figure 2. Composite production stages of the study.

MATERIAL AND METHODS

Preparation and Characterization of Olive Pomace Oil Maleate (OPOMA)

Olive pomace oil maleate (OPOMA) was prepared from pomace oil to be used in the production of PLA composites (Fig. 1). In the production of OPOMA, maleic anhydrite (MA) was used as 20% by weight of olive pomace oil and dicumyl peroxide (DCP) was used as 3% by weight of MA. In the study, DCP was used as a free radical initiator. The OPO-MA-DCP mixture of the specified weights was mixed in the mixer at 170 °C for 2 hours to complete the reaction. The experimental conditions for OPOMA preparation were adjusted based on study of Kiangkitiwan and Srikulkit [14].

FTIR analyzes of OPOMA were performed using the ATR method on the Thermo Scientific Nicolet iS5 FT-IR spectrometer. For the ATR method, the monolithic diamond crystal ID 7 module of the FTIR device was used. In the ATR analysis, reading was performed in the computer program after the tip of the ID 7 module was adjusted to completely contact the sample. ^{1}H NMR spectra of OPOMA was conducted with JEOL JNM-ECP500 spectrometer at 500-MHz.

Composite Production and Characterization

Olive pomace obtained with ionic liquid pretreatment (OP-IL) in the previous studies of the authors [3] and OPOMA were used in the production of composites with a biodegradable polymer of PLA. Composites were prepared in a twin-screw extruder using the method shown in Figure 2. Composite production studies started by first producing control composite samples using only PLA plastic. The composite was obtained by mixing 95PLA+5OP-IL by weight in a twin-screw extruder at 190 °C for 10 minutes. Under the same experimental conditions, the effect of OPOMA on mechanical properties of the composite was investigated on the samples produced by adding 0.5%, 1% and 2% ratio to PLA + OP-IL mixtures.

The tensile strength (MPa), modulus of elasticity (GPa), breaking stress and unit elongation values of the produced dumbbell shaped composite samples were measured using the Minebea Mitsumi (Load test standard: 1kNB-S100) brand tensile-compression test device. The test force was set as 1 kN and the tensile speed was set as 10 mm/min. During the test, the elongation in the composites was measured using an extensometer.

RESULTS AND DISCUSSION

The functional groups of both OPO and OPOMA were identified by FTIR and ^{1}H NMR analysis (Fig. 3). Both OPO and OPOMA samples have peaks between 2800–3100 cm^{-1} which represent -C-H, CH_2, CH_3 and cis/trans=C–H stretching bonds. These results also matched up with the olive oil FTIR spectrum given in the literature [14]. Moreover, C=O bonds representing the ester, aldehyde, ketone, anhydride and/or free fatty acids were observed at 1744 cm^{-1} wave number for OPO and OPOMA [15, 16]. Vibration of CO ester bonds and bending vibration of the -OH group were observed at 1160 cm^{-1} and 1033 cm^{-1}, respectively [17]. The different bond observed in OPOMA comparing to the OPO at 1775 cm^{-1} and 1850 cm^{-1} represents the symmetric and asymmetric stretching of C=O in the pendent anhydride group [14]. It was not observed any peak at 3500 cm^{-1} because of the opening anhydride ring, which means that anhydride ring remains intact. This result also can be confirmed by ^{1}H NMR spectra of OPOMA (Fig. 3). Methylene protons of anhydride pendant were observed at 2.60–2.70 and at 2.80–2.90 ppm [14]. Therefore, it can be emphasized that OPOMA were successfully synthesized from OPO.

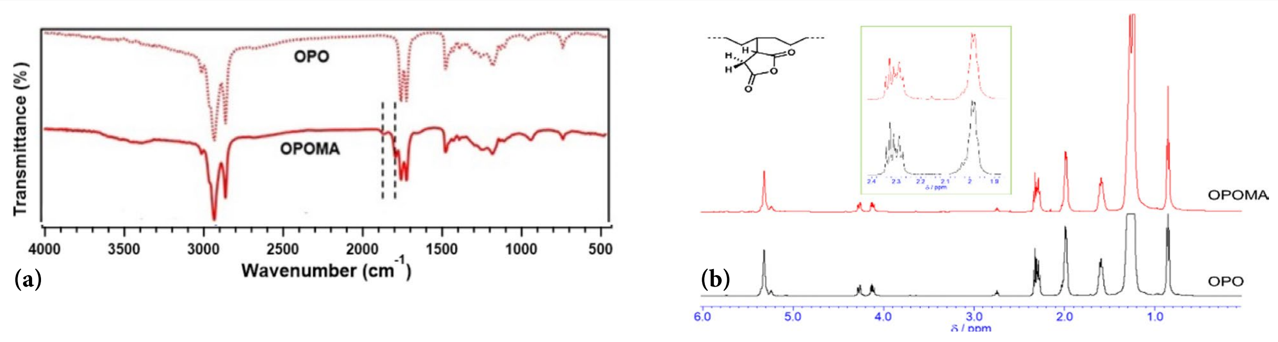

Figure 3. **(a)** FTIR and **(b)** 1H NMR spectra of OPO and OPOMA.

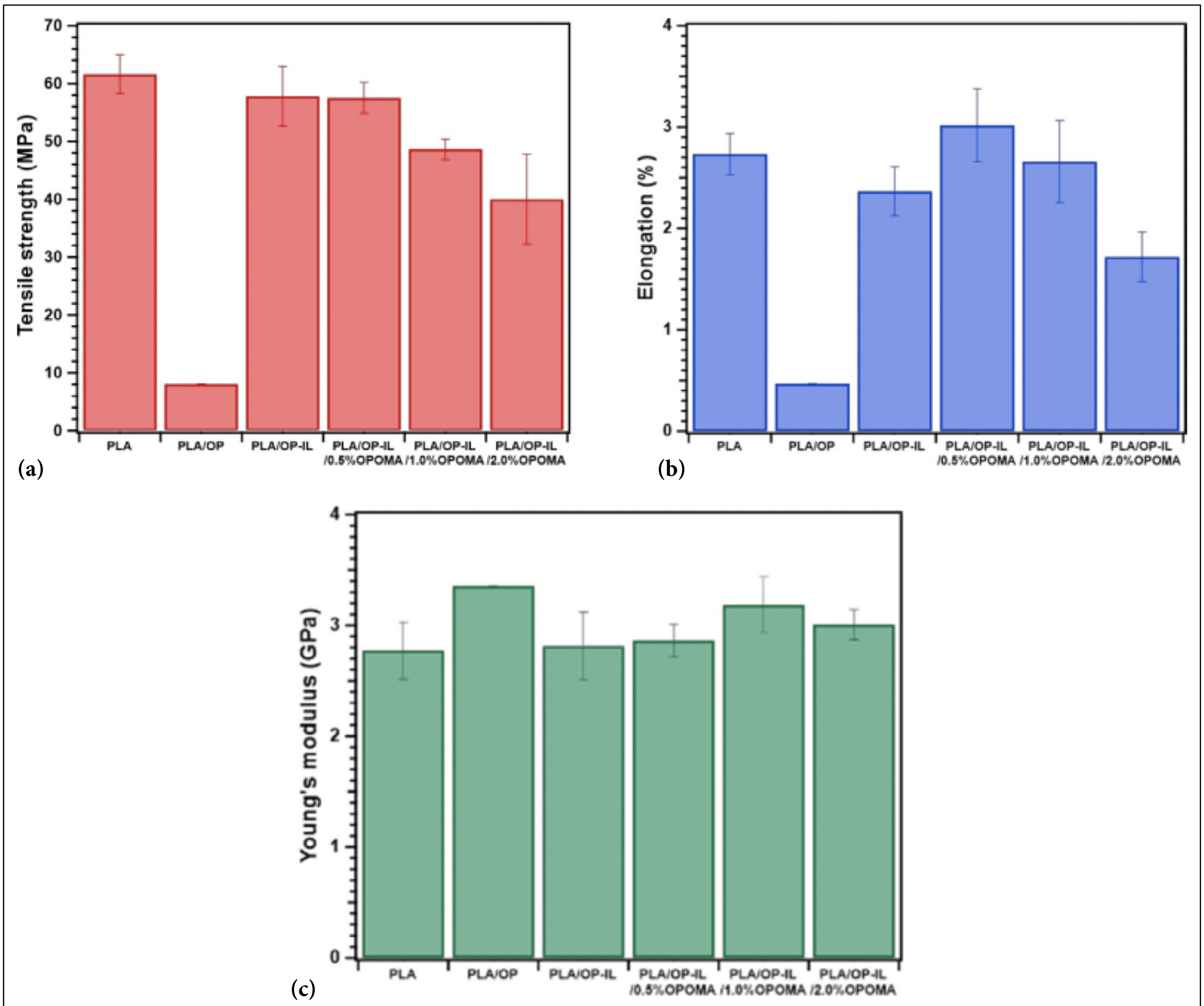

Figure 4. Mechanical properties of PLA+OP composites **(a)** tensile strength **(b)** elongation **(c)** elasticity modulus.

Mechanical properties of the obtained green composites were shown in Figure 4. The tensile strength of the PLA+OP composite increased remarkably with the addition of OP-IL. While the tensile strength of the PLA+OP mixture was approximately 10 MPa; the tensile strength value of PLA+OP-IL was around 60 MPa (Fig. 4a). This shows that the ionic liquid pretreatment applied to the pomace partially removes the hemicellulose and lignin structures in the OP and cellulose in the structure strengthens the interfacial bonding of PLA matrix and OP particles. On the contrary, increment of the OPOMA in the mixture decreased the tensile strength of the composites. Similar to the tensile strength, the elongation value increased with the application of ionic liquid pretreatment to OP. The addition of 0.5% OPOMA had an increasing effect on the elongation value. Increasing the OPOMA percentage in the mixture from 0.5% to 3% caused a decrease in the tensile

Table 1. Mechanical properties of PLA composites with different reinforcement materials

Reinforcement material (wt%)	PLA matrix (wt%)	Treatments for biomass	Tensile strength (MPa)	Elongation (%)	Young's modulus (GPa)
5% Pine [21]	95%	–	56.0±1	1.9±0.2	4.3±0.3
5% Cellulose [22]	95%	–	63.4±1.1	N/A	3.9±0.1
5% Rapeseed straw [23]	95%	–	50.9±0.6	3.1±0.31	2.8±0.06
10% Rapeseed straw [23]	90%	–	48.3±1.4	2.35±0.15	4.08±0.02
15% Banana-15% Sisal [24]	70%	Chemical treatments with NaOH for 2 hours	40.0	N/A	4.1
20% Jute–20% Coir [25]	60%	Silane and NaOH treatments	65.0	N/A	3.2
2% Algae [26]	98%	–	58.0±1	3.5 0±0.3	4.0±0.1

elongation value (Fig. 4b). This decrement observed in elongation value with the increment of OPOMA percentage shows that a phase separation occurs in the composite mixture when a high proportion of OPOMA is used. Similar to the presented study result, Lv et al. [18] emphasized that mechanical properties can be increased up to 144% with reactive compatibilizing agent at optimum dosage. However, it was reported in the same study that excess dosage can result in the staying compatibilizing agent at interface phase and thereby, decrement of the tensile strength because of the increment of the distance between chains. Similarly, Poletto [19] reported that mechanical, thermal and/or morphology of composite can successfully be enhanced with maleated soybean oil (MASO) produced with soybean oil and MA at optimum dosages. Elastic modulus showed less change compared to other mechanical properties. The highest elastic modulus value was observed in the PLA+OP mixture (Fig. 4c). These results indicated that, when the raw OP itself is intended to be used as additive in PLA composites, it is not feasible in terms of mechanical properties. However, when the modification proposed in this study was applied, then the mechanical properties that are comparable to the neat PLA can be achieved. When some part of the matrix polymer could be replaced with such a modified waste material, this would help to reduce the consumption of raw polymer material, to increase the use waste material in circular economy and to reduce its discharge into the environment.

Mechanical properties of PLA composites obtained with different reinforcement materials were presented in Table 1. While tensile strength of composites produced with untreated biomasses were between 50–63 MPa, tensile strength of composites addition with treated and/or combination of different biomasses were 40–65 MPa. As seen in Figure 4, tensile strength of PLA+OP-IL+OPOMA composites coincided with the literature values. Moreover, higher mechanical properties, especially for 0.5% OPOMA condition, were obtained in presented study as compared to PLA composites produced with treated reinforcement materials (Table 1). Similar to the presented study, Arbelaiz et al. [20] modified PLA-sisal and flax fiber filler interface with MA in the presence of DCM and it was stated that higher tensile strength was obtained at lower ratios of compatibilizer such as 1%. This can be attributed to degradation of matrix in the case of over the optimum dosage of the reactive compatibilizing agent [19, 20]. Therefore, it can be emphasized that synthesized compatibilizer, namely OPOMA, can be effectively used in PLA-OP composite.

CONCLUSION

In this study, a novel compatibilizer (OPOMA) was produced from olive pomace oil for the first time and used in the production of composites with a biodegradable polymer of PLA. New symmetric and asymmetric C=O bands in the FTIR spectrum of OPOMA, unlike olive oil, show that OPOMA has been synthesized successfully. While the addition of low doses of OPOMA to PLA+OP-IL composites increased the tensile elongation value, tensile strength did not change. The elasticity modulus showed less change compared to other mechanical properties. When the mechanical properties of the composites obtained within the scope of the study were evaluated, it was observed that they matched up with the studies in the literature and more successful results were obtained compared to some pre-treated biomass. Therefore, it can be emphasized that oil maleates of lignocellulosic biomasses can be promising compatibilizer for biodegradable composite matrices and OPOMA can be used as compatibilizer in biodegradable polymer matrixes. Moreover, mechanical properties of PLA-OP composites were successfully enhanced with the addition of both OP-IL and OPOMA. Thereby, with these investigated mechanical properties, the produced composites can be good alternative for specially building-construction and automotive sectors in which composite materials are commonly used in the world. These composite materials can also be preferable to these sectors since the additive material is sustainable, low-cost, easily available, environmentally friendly as it is produced in high quantities, and thus contributes to low-carbon composite production and to the circular economy.

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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.

USE OF AI FOR WRITING ASSISTANCE

Not declared.

ETHICS

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

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Research Article

Life cycle assessment of energy production from municipal solid waste: İstanbul case

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ABSTRACT

Several methods are used during waste management: landfill, incineration, composting, anaerobic digestion, pyrolysis, and recycling etc. In particular, the use of biogas formed through anaerobic digestion in energy production and the energy obtained through the incineration process is very effective in turning the negative effects of wastes into positive ones. In this study, the effects of three different waste management scenarios were examined from a life cycle perspective. According to the results, scenario1 (landfill and incineration), scenario2 (landfill, incineration, and anaerobic digestion), and scenario3 (landfill, anaerobic digestion, and recycle) produced emissions of 3233.1, 328.8, and -848.9 kg of CO_2eq, respectively. Accordingly, and in accordance with the results of the previous studies, it is observed that the landfill application gave the worst environmental result, the incineration and anaerobic digestion applications reduce the environmental effects, and the recycling application provides environmental benefits. It is concluded that the best environmental practice is plastic and metal recycling.

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INTRODUCTION

Urbanization has many potential benefits, including increased access to jobs, education, healthcare, and other services. However, it can also lead to overcrowding, traffic congestion, pollution, and other challenges. Excessive consumption, meanwhile, can drive economic growth and innovation, but can also lead to resource depletion, environmental degradation, and social inequality. Excessive consumption refers to the trend of increased demand for goods and services, often driven by factors such as population growth, economic development, and technological advancements. This trend has been on the rise in recent years, as global populations continue to grow and economies continue to expand. Industrialization, increasing population growth, and economic development can contribute to the generation of large amounts of municipal solid waste (MSW) - which refers to the waste produced by households, commercial and institutional establishments, and other non-industrial sources. As economies grow, the demand for goods and services increases, resulting in the production of more waste. In addition, urbanization and population growth can further exacerbate this problem, as more people live in urban areas where waste generation is typically higher. Industrialization can also lead to the generation of hazardous waste from manufacturing and other industrial processes, which can be difficult and expensive to dispose of safely [1, 2]. The increase in people's welfare

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level and quality of life causes an increase in solid waste production per capita. Owing to the increasing population and rapid industrialization, municipal solid waste management (MSWM) has become a significant problem faced by countries. The municipal solid waste consists of both biodegradable and non-biodegradable parts of organic and inorganic materials [3]. Biodegradable waste refers to organic materials that can break down naturally over time, such as food scraps, yard waste, and paper products. Non-biodegradable waste, on the other hand, includes materials that do not break down naturally, such as plastics, metals, and glass. To eliminate these problems, it is urgent to improve environmentally friendly methods in MSW management. Therefore, landfill, anaerobic digestion, and incineration methods have acquired importance to minimize MSW.

The landfill is the most common method of waste management worldwide and has served as final waste recipients for municipal waste, industrial residues, recycling waste and wastewater sludge [4]. A landfill is a site where MSW and other types of waste are disposed of in the ground. Landfills are a common method of waste disposal and are typically managed by municipal or regional waste management authorities. The wastes accepted to the landfills during the operation phase are stored at a security level that will not damage the structural strength of the site and will not cause slips and collapses on interior and exterior slopes. It must be ensured that the stability of the ground is such that it will not damage the impermeability layer [5, 6].

Anaerobic digestion is a process in which complex organic materials are decomposed under anaerobic conditions and fermented into volatile fatty acids (VFA) by acid bacteria. VFA is then consumed by methanogenic bacteria and converted to methane gas This process produces biogas, a mixture of methane (CH4) and carbon dioxide (CO_2), as well as a nutrient-rich digestate that can be used as a fertilizer [7]. The end product of anaerobic digestion contains biogas (50–75% CH4, 50–25% CO_2 and the remainder are impurities) and an organic residue [8, 9].

The incineration method has become an effective method of dealing with MSW due to its bulking and weight reduction effects [10]. Incineration is a waste management method that involves the combustion of MSW at high temperatures, typically between 800–1000 degrees Celsius, to produce energy and reduce the volume of waste that must be disposed of in landfills. Incineration has the advantage of significantly reducing the volume of MSW that must be disposed of, which can help to extend the lifespan of landfills. In addition, incineration can also generate renewable energy, reducing the reliance on fossil fuels. Even so, since heavy metals and organic pollutants in the ashes resulting from incineration pose a serious threat to the ecosystem and biological community including human health, they should be carefully examined and investigated [11].

Life cycle assessment (LCA) is an innovative approach that can be used in many different areas and is frequently used in the accurate and comprehensive assessment of the cumulative and holistic environmental impacts of MSWM processes. LCA can help to identify the environmental trade-offs associated with different waste management strategies and can provide insight into opportunities for reducing the environmental impact of waste management [12]. LCA typically considers a range of environmental impacts, including greenhouse gas emissions, energy consumption, water use, and waste generation. LCA evaluates all sub-processes of a product system from cradle to grave and provides a calculation of the environmental loads caused by these processes. LCA consists of five phases: goal definition, scope definition, inventory analysis, impact assessment, and interpretation. Sometimes, the goal and scope definition can be reviewed in a single topic [13]. This phase is considered very important as it will directly affect the work to be carried out in other stages. Then, an inventory is created by collecting the data to be used in the study, and then the impact assessment is carried out by making the necessary calculations. Finally, the obtained outputs are interpreted and the final result is reached [14].

Babu et al. [15] reported that a literature review conducted on LCA studies of landfills in Europe identified waste composition, climatic conditions, and landfill management as the most significant factors that influence the environmental impacts of landfill sites. Comparative analyses of landfilling against other MSWM options by Dong et al. [16] showed that landfilling was associated with greater global warming potential (GWP) than other waste management options, primarily due to increased methane and carbon dioxide emissions. LCA has been extensively utilized in forecasting MSW technology. Babu et al. [15] undertook an LCA comparison among four distinct MSWM scenarios for India, encompassing open dumping, storage sans gas recovery, storage with gas recovery, and bioreactor storage. Their findings favoured bioreactor storage over other options. In a similar vein, delineated the environmental impacts associated with six alternative scenarios in India. They observed that Incineration, composting, anaerobic digestion, recycling, landfilling, and landfilling with biogas collection yielded the highest reductions in environmental impacts, especially with a recycling rate of approximately 90% [16]. Rana et al. [17] scrutinized the impacts of diverse MSW disposal methods in India via LCA and determined that MSW Incineration (MSWI) exhibited the most promising outcomes for mitigating environmental impact and reducing greenhouse gas emissions. These studies collectively underscore that each city possesses its own unique dynamics, leading to disparate outcomes in LCA MSW analyses. The results of a similar study conducted in India presented that integration of material recovery, composting, and sanitary landfill provides the most environmentally friendly solution [18, 19].

Although all three disposal methods used in this study have their advantages, landfill is considered environmentally risky when used alone (where no biogas production process is available), and incineration is generally considered better for global warming than landfill [20]. Anaerobic digestion, on the other hand, is considered to be very beneficial in terms of the environment as a disposal method that supports biogas and therefore energy production [5, 21–23].

This study aims to examine the environmental effects of different MSWMs (incineration, anaerobic digestion, and recycling) that allow energy production, together with landfill. The application of LCA scenarios for MSWM management in Türkiye involves evaluating the environmental impacts of different waste management options throughout their entire life cycle. The scenarios include various MSWM options, scenario1 (landfill and incineration), scenario2 (landfill, incineration, and anaerobic digestion), and scenario3 (landfill, anaerobic digestion, and recycling). Thus, the dimensions of environmental gain, especially through the production of biogas from organic waste, will be examined from the perspective of LCA.

The main objective of the study is to reveal the waste-to-energy potential of a city like Istanbul, which generates a large amount of waste. For this purpose, different scenarios were developed, but all of them favoured methods (incineration, anaerobic digestion, and recycling) that can either generate energy or save energy. In addition to these methods, the landfill was included in the scenarios as a control for the utilisation of waste that cannot be utilised for energy. In this context, it is aimed to draw attention to the potential in large cities by revealing the extent of energy that can be obtained from waste.

MATERIALS AND METHODS

LCA is widely used for calculating the environmental impacts of waste management methods and it provides numerous benefits for especially observing the differences between MSW scenarios, which include various methods. In the study, SimaPro 9.3.0.2 package program and ReCiPe 2016 method in this program were used for LCA calculations [24]. On account of calculating the results of the waste management processes, the previously calculated input-output data for each waste disposal method is defined in the system in the Processes title. After, the wastes are defined in the program under the Product Stages title. Then, the information of which disposal method will be used in the treatment of which waste is defined, and finally, the desired LCA method is selected, and the results are reached. The main reason for the choice of SimaPro software in the study is the familiarity of the authors with this software, but also the diversity of the content of the Ecoinvent database that SimaPro utilises.

Scenario Setting

The scenarios are determined to measure the combinations of the impacts of the landfill and energy production from anaerobic digestion and incineration processes. These scenarios were selected in accordance with the previous literature and were optimized to reach the most different results. The potential outputs were also considered.

Scenario-1 (S1): Situation where all combustible waste is incinerated, and ash and residual waste is stored in a landfill. This approach is often referred to as "waste-to-energy" (WTE) or "energy-from-waste" (EFW).

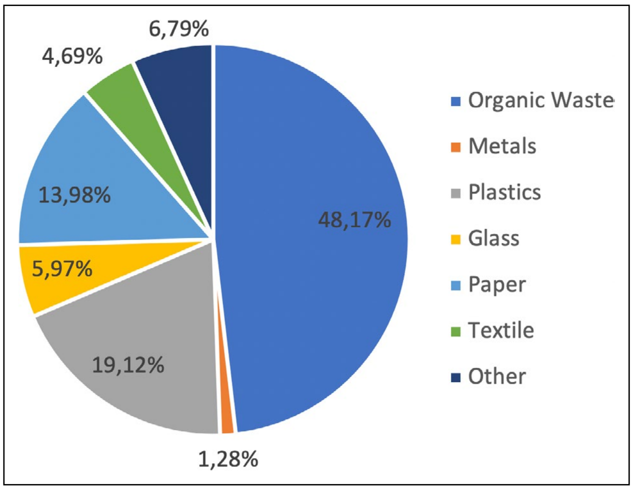

Figure 1. İstanbul 2020 waste composition.

Table 1. Energy production of disposal methods

Scenarios	Disposal method	Electric energy	Heat energy
Scenario1	Incineration	181.01 kWh	1678.78 MJ
Scenario2	Anaerobic digestion	1153.19 kWh	516.77 MJ
	Incineration	181.01 kWh	1678.78 MJ
Scenario3	Anaerobic digestion	1153.19 kWh	516.77 MJ

Scenario-2 (S2): The situation in which all organic waste is treated with anaerobic digestion, all combustible waste is incinerated and the remaining waste is stored in a landfill.

Scenario-3 (S3): The situation in which all organic waste is treated with anaerobic digestion, all recyclable waste is recycled, and the remaining waste is stored in a landfill.

Data Collection

The waste composition used in the study was obtained from the wastes collected in Istanbul in 2020 and is presented in Figure 1. The data were taken from the Provincial Environmental Status Report published by the Istanbul Provincial Directorate of Environment.

In all three scenarios, the input (water as rain, oxygen (O_2), diesel fuel)-output (wastewater as equal to precipitation, CO_2, water, sulphur dioxide (SO_2), nitrogen oxides (NO_x) data of the relevant disposal methods were introduced to the program. Information on the amount of energy produced from the disposal methods, which is the main purpose of the study, is presented in Table 1. Thus, the life cycle inventory, which is one of the main components of an LCA study, was completed. The inventory consists of waste composition, input and output data, and the energy produced as a result of the relevant disposal method.

Functional Unit

A functional unit is a measure of the performance of a product or service that is used as a reference point in an LCA. The functional unit is a key component of the LCA because it defines the basis for comparing different products or services in terms of their environmental impacts. 1 t of waste was chosen as the functional unit. This means that the environmental impacts of managing 1 tonne of waste will be assessed and compared across different waste management options. By using a common functional unit, it is possible to compare the environmental impacts of different waste management options on an equal footing. It is assumed that the incineration process does not involve any energy recovery.

System Information

Considering the ongoing efforts of national and international organizations to reduce greenhouse gas emissions and the declarations taken by all states that are party to the United Nations Framework Convention on Climate Change (UNFCCC), decision-makers are turning to different disposal methods and increasingly assessing the GWP. Waste management is important because of its environmental effects. Landfill leachate is produced by excess rainwater that percolates through layers of waste from the landfill. The resulting liquid is a complex mixture of organic and inorganic compounds, including nutrients, heavy metals, pathogens, and other pollutants [25]. Once a landfill is closed, it will continue to produce contaminated leachate, which can last 30–50 years. In general, leachate contains large amounts of organic matter and may also contain heavy metals that pose a major threat to the surrounding soil, groundwater and even the surface. When precipitation occurs, the rain comes into contact with solid waste and as a result, forms leachate. The leachate may contain large amounts of organic content, heavy metals and inorganic salts, so precipitation can have a direct impact on the quality and quantity of leachate produced by a landfill. When rainwater percolates through the layers of waste in a landfill, it can dissolve and mobilize organic and inorganic pollutants, including heavy metals and salts, and carry them along with the leachate. This can lead to an increase in the concentration of these pollutants in the leachate, potentially leading to greater environmental impacts if the leachate is not properly managed. Istanbul, which hosts the Asian and European continents, has a transitional climate between the Black Sea and the Mediterranean and is one of the cities that receive the most precipitation in the Marmara Region. The lowest temperature in the city is -11, the highest temperature is +40 degrees throughout the year, and the average relative humidity is 75%. Although all months of the year are humid in Istanbul, the period when the city has the highest humidity is determined as December-January with a rate of 80–85%. Although snowfalls are not frequent due to the high humidity, there is little snowfall in the period between December and March. Landfill Gas (LFG) is a natural by-product of the anaerobic decomposition of organic substances. LFG includes roughly 50 to 55 per cent methane and 45 to 50 per cent carbon dioxide and contains less than 1 per cent non-methane organic compounds (NMOCs) and traces of inorganic matter [26].

The production of LFG is a natural result of the decomposition of organic waste materials in landfills. As waste materials break down, they release gases, including methane and carbon dioxide, into the surrounding air. In landfills, however, these gases are trapped by the layers of waste above and around them, leading to the build-up of LFG.

Figure 2. Flowchart for the method.

As a microbial ecosystem, the anaerobic digestion process has different stages of digestion, starting with the breakdown of complex organic compounds and ending with the generation of biogas as the final product. Anaerobic digestion is a good option for stabilizing sludge and is the most energy-efficient and environmentally useful technique for bioenergy production. The sludge produced after anaerobic digestion is mostly inert, less in volume and less hazardous than untreated sludge.

Municipal solid waste incineration is standard practice to reduce waste disposal. This is because incineration technology provides a more efficient way of reducing the amount of municipal solid waste that needs to be landfilled. The incineration of municipal solid waste can reduce its mass by 70% and volume by 90% [27], as well as electricity and heat recovery [10]. The primary goal of incineration is to reduce the volume and weight of waste and to minimize the need for landfill space.

Although incineration can reduce the volume of waste and generate energy, it has been a controversial method of waste disposal due to the potential environmental and health risks associated with emissions from incineration facilities. Incineration can release pollutants such as dioxins, furans, and heavy metals, which can have harmful effects on human health and the environment.

A flowchart for the method implemented in the study is presented below as Figure 2.

RESULTS AND DISCUSSIONS

Results

The incineration of waste necessitates the use of chemical inputs for flue gas treatment, including hydrochloric acid, lime, and ammonia, as well as diesel and electricity to power the incinerator. Following incineration and the cleaning of flue gas, the secondary waste in the form of slag and fly ash is recovered and necessitates treatment. In S1, the incineration of combustible waste in a WTE facility can generate electricity and/or heat, which can be used to power homes and businesses. In addition, the ash generated from the incineration process can be landfilled, reducing the volume of waste that must be disposed of in a landfill. However, there are also concerns associated with this approach. Incineration facilities can emit air pollutants, including dioxins and other harmful chemicals,

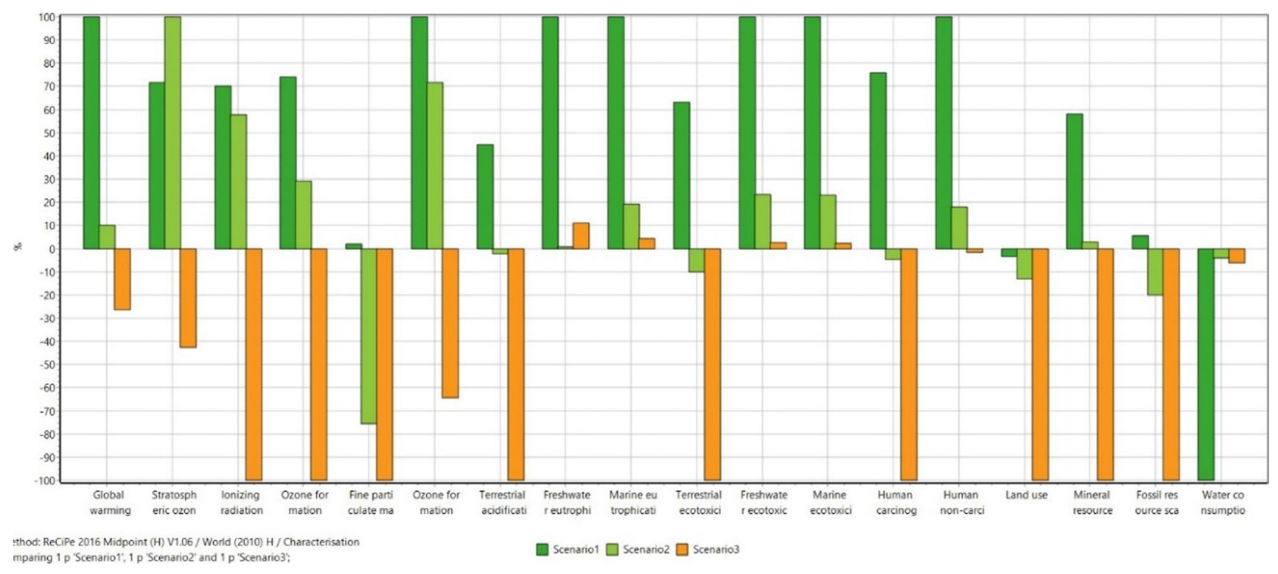

Figure 3. Comparison of the scenarios in midpoint categories.

which can have negative impacts on human health and the environment. In addition, while the ash generated from incineration is less voluminous than the original waste, it may contain concentrated levels of heavy metals and other contaminants, which can pose risks to human health and the environment if not properly managed.

In S2, anaerobic digestion is a biological process that involves the decomposition of organic material in the absence of oxygen, producing biogas and a nutrient-rich digestate. The biogas can be used to generate electricity and heat, while the digestate can be used as a fertilizer or soil amendment. The incineration of combustible waste can generate energy in the form of electricity or heat and can reduce the volume of waste that must be disposed of in a landfill. The remaining waste, which is not suitable for anaerobic digestion or incineration, is disposed of in a landfill. This waste may include non-combustible waste, hazardous waste, and other materials that cannot be effectively managed through other waste management strategies. While this waste management strategy has advantages, such as reducing the volume of waste that must be landfilled and generating renewable energy, it also has potential drawbacks. Incineration can emit air pollutants, such as dioxins and particulate matter, which can negatively impact human health and the environment. Landfills can also generate greenhouse gas emissions, including methane, which contributes to climate change.

In S3, anaerobic digestion is a biological process that involves the breakdown of organic material. The recoverable fraction of the biodegradable portion of MSW can be collected and subjected to anaerobic digestion, after which the digester can be employed as a substitute for chemical fertilizers in agricultural fields. The resulting biogas can be used in electricity generation since it can be directly incorporated into the grid. Although the use of biogas as heat with central heating or biofuel has not been considered in the present context due to the absence of appropriate infrastructure, additional research will be necessary to determine the most effective use of biogas within a regional context. In the absence of oxygen, producing biogas and a nutrient-rich digestate. The biogas can be used to generate electricity and heat, while the digestate can be used as a fertilizer or soil amendment. Recycling all recyclable waste can reduce the amount of waste that must be disposed of in a landfill, and can conserve natural resources by reducing the need for virgin materials. Recycling can also help to reduce greenhouse gas emissions associated with the extraction, processing, and transportation of raw materials. The remaining waste, which is not suitable for anaerobic digestion or recycling, is disposed of in a landfill. This waste may include non-recyclable materials, hazardous waste, and other materials that cannot be effectively managed through other waste management strategies. This scenario represents a waste management hierarchy known as "reduce, reuse, recycle" where the priority is to reduce waste generation, followed by the reuse of products and materials, and the recycling of as much waste as possible. While this waste management strategy has advantages, such as reducing the volume of waste that must be landfilled and conserving natural resources, it also has potential drawbacks. Landfills can generate greenhouse gas emissions, including methane, which contributes to climate change. In addition, the transport and processing of recyclable materials can generate greenhouse gas emissions and other environmental impacts.

Midpoint categories are typically used in LCA to help quantify the potential environmental impacts of a product or activity. The midpoint categories used in LCA depend on the specific impact categories of interest. It would be feasible to evaluate the impact of each safeguard subject by comparing the outcomes of scenarios based on the results of individual midpoint and endpoint categories.

Table 2. Environmental impacts of the scenarios

Impact categories	S1	S2	S3	Unit
GWP	3233.1	328.8	-848.9	kg CO_2eq
SOP	0.0007	0.001	-0.0004	kg CFC11 eq
IR	10.6	8.7	-15.1	kBq Co-60 eq
OF	1.8	0.7	-2.5	kg NO_xeq
FPMF	0.08	-2.9	-3.9	kg $PM_{2.5}$eq
TA	3.9	2.9	-2.6	kg SO_2eq
FEU	1.9	-0.1	-4.2	kg P eq
MEU	1.5	0.01	0.2	kg N eq
TE	0.5	0.1	0.02	kg 1,4-DCB
FEC	1008.7	-163.6	-1595.5	kg 1,4-DCB
MEC	287.1	67.0	7.8	kg 1,4-DCB
HCT	376.1	86.7	8.9	kg 1,4-DCB
HNCT	64.4	-4.1	-84.9	kg 1,4-DCB
LU	5927.1	1067.4	-101.03	m^2a crop eq
MSS	-7.3	-27.8	-212.8	kg Cu eq
FSS	2.5	0.1	-4.3	kg oil eq
WC	24.4	-90.6	-449.1	m^3

GWP: Global warming potential; SOP: Stratospheric ozone depletion; IR: Ionizing radiation; OF: Ozone formation; FPMF: Fine particular matter formation; TA: Terrestrial acidification; FEU: Freshwater eutrophication; MEU: Marine eutrophication; TE: Terrestrial ecotoxicity; FEC: Freshwater ecotoxicity; MEC: Marine ecotoxicity; HCT: Human carcinogenic toxicity; HNCT: Human non-carcinogenic toxicity; LU: Land use; MSS: Mineral source scarcity FSS: Fossil source scarcity; WC: Water consumption.

Figure 3 and Table 2 present the results of the environmental impacts of all three scenarios visually and numerically, respectively. The sub-categories presented in Table 2 and Table 3 are referred to the following abbreviations: global warming potential (GWP), stratospheric ozone depletion (SOP), ionizing radiation (IR), ozone formation (OF), fine particular matter formation (FPMF), terrestrial acidification (TA), freshwater eutrophication (FEU), marine eutrophication (MEU), terrestrial ecotoxicity (TE), freshwater ecotoxicity (FEC), marine ecotoxicity (MEC), human carcinogenic toxicity (HCT), human non-carcinogenic toxicity (HNCT), land use (LU), mineral source scarcity (MSS), fossil source scarcity (FSS), water consumption (WC). These midpoint categories are useful for comparing the environmental impacts of different waste management strategies and identifying areas where improvements can be made to reduce the overall environmental impact of MSW.

As seen in Figure 3, it is understood that S3 is a more environmentally friendly approach in all categories except the water consumption category. The reason for this is that the recycling process is also implemented. Recycling is a key element in sustainable waste management as it aims to reduce the amount of waste sent to landfill or incineration, conserve natural resources, and reduce the environmental impact of waste disposal. On the other hand, S2, in which anaerobic digestion and incineration methods are used in addition to landfill management, showed much better environmental performance than S1, which is based only on landfill and incineration methods. Anaerobic digestion and incineration are two waste management methods that are commonly used to treat organic waste. The potential environmental impacts of these methods can be assessed using midpoint categories, which help to quantify the environmental impact of the waste treatment process. Based on this information, it can be said that landfill is the most environmentally problematic method among the methods evaluated in this study. In S2, where the anaerobic digestion method is used together with incineration, a serious environmental performance increase is observed compared to S1, but it is also seen that the values cannot go down to negative levels, that is, a full environmental gain cannot be achieved. However, S3, where recycling is applied together with anaerobic digestion, is the scenario where negative values, that is, a complete environmental gain, are obtained. Based on Figure 3, it is evident that S2 and S3 result in the greatest adverse impact in the Human Health damage category. process is responsible for the S3 scenario being the most unfavourable in this study.

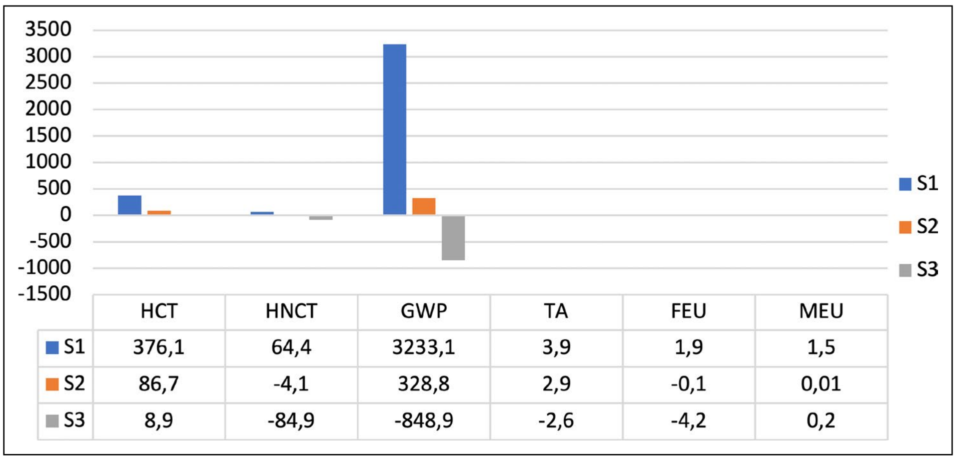

Figure 4. Comparison of some environmental impacts.

Table 3. Environmental impacts of the scenarios

Impact categories	Total	Landfill	Anaerobic digestion	Glass recycle	Metals recycle	Paper recycle	Plastics recycle	Unit
GWP	-848,9	175,4	-299,9	-75,3	-286,3	-19,4	-343,4	kg CO_2 eq
SOP	-0,0004	0.000004	0,0004	-0.00003	-0.00006	-0.00001	-0,0007	kg CFC11 eq
IR	-15,1	0,2	2,8	-2,4	-1,9	-1,8	-12,06	kBq Co-60 eq
OF	-2,5	0,02	-0,8	-0,2	-0,7	-0,2	-0,6	kg NO_x eq
FPMF	-3,9	0,007	-2,9	-0,2	-0,6	-0,07	-0,2	kg $PM_{2.5}$ eq
TA	-2,6	0,02	-0,8	-0,2	-0,8	-0,2	-0,7	kg SO_2 eq
FEU	-4,2	0,02	-1,6	-0,4	-1,3	-0,1	-0,8	kg P eq
MEU	0,2	0,7	-0,3	-0,02	-0,1	-0,03	-0,04	kg N eq
TE	0,02	0,06	-0,02	-0,001	-0,006	-0,001	-0,005	kg 1,4-DCB
FEC	-1595,5	31,5	-201,4	-211,2	-210,2	-153,1	-851,1	kg 1,4-DCB
MEC	7,8	30,9	-3,2	-2,08	-6,9	-1,09	-9,9	kg 1,4-DCB
HCT	8,9	40,6	-4,6	-2,8	-9,6	-1,5	-13,1	kg 1,4-DCB
HNCT	-84,9	2,4	-16,1	-2,6	-52,5	-2,2	-13,9	kg 1,4-DCB
LU	-101,0	645,5	-232,2	-51,2	-241,9	-33,9	-187,2	m^2a crop eq
MSS	-212,8	0,3	-15,1	-5,7	-3,3	-186,7	-2,4	kg Cu eq
FSS	-4,3	0,07	-0,07	-0,2	-3,06	-0,1	-0,9	kg oil eq
WC	-449,1	1,3	-88,1	-19,7	-58,9	-4,7	-278,9	m^3

GWP: Global warming potential; SOP: Stratospheric ozone depletion; IR: Ionizing radiation; OF: Ozone formation; FPMF: Fine particular matter formation; TA: Terrestrial acidification; FEU: Freshwater eutrophication; MEU: Marine eutrophication; TE: Terrestrial ecotoxicity; FEC: Freshwater ecotoxicity; MEC: Marine ecotoxicity; HCT: Human carcinogenic toxicity; HNCT: Human non-carcinogenic toxicity; LU: Land use; MSS: Mineral source scarcity FSS: Fossil source scarcity; WC: Water consumption.

LCA impact categories are a set of environmental indicators that are used to assess the potential environmental impacts of a product or service throughout its entire life cycle. These impact categories are typically based on the different environmental issues that can arise from a product or service and are used to provide a standardized method for comparing different products or services.

As can be seen from Table 3, the best positive contribution to the global warming category is the recycling of plastics. Recycling can help reduce greenhouse gas emissions by reducing the need for virgin materials and the energy required to extract, process, and transport them. It is followed by the recycling of metals by anaerobic digestion. When the table is examined as a whole, it can be seen that plastic recycling and metal recycling bring very beneficial results from an environmental point of view in most of the impact categories. In addition, paper recycling can also be considered a very useful process. In addition, the anaerobic digestion process has a remarkable effect on reducing the environmental burden.

Accordingly, considering a scenario where only recycling is not possible, operating the anaerobic digestion process for organic wastes, recycling recyclable wastes and addition to these, incineration can be interpreted as an environmentally beneficial application.

Figure 4 presents a summary of comparison for toxicity, global warming potential, acidification, and eutrophication.

DISCUSSION

The outcomes of an LCA analysis are often affected by the input parameters used in the assessment. Thus, the input-output (sources from nature, avoided products, energy output etc.) data was carefully calculated and added to the software. Besides, the appropriate methods were selected among various similar method, such as landfill, recycle, composting, and anaerobic digestion.

The main limitation of this study is the difficulty to reach the waste composition. Since municipalities do not keep proper records and large amounts of waste are generated, there may be a certain degree of error in the calculations.

Integrating different MSMWs may provide a better environmental performance as shown in [17, 18]. Landfill disposal has a significant impact on the GWP. Studies have found that storage emits -0.07 to 0.16 kg CO_2eq/kg and 0.25–0.45 kg CO_2eq/kg [28]. Landfill disposal can have a significant impact on the GWP due to the release of methane, a potent greenhouse gas, during the decomposition of organic waste in the landfill. CH4 has a much higher global warming potential than CO_2 over a 20-year time horizon, although it breaks down more quickly in the atmosphere. Recycling makes significant support to both direct and avoided impacts across all impact categories [29]. Anaerobic digestion is widely recommended as an ideal disposal method for organic wastes, as it is suitable for the circular economy due to the possibility of material and energy recovery. At the same time, composting can be a major source of greenhouse gases when not done with the appropriate ratio and content [12]. According to the LCA results of (Slorach et al. [29]), composting has been identified as the worst option for treating food waste in the United Kingdom. It has been observed that anaerobic digestion systems cause a significant negative impact in terms of the GWP effect [30] It has been observed that the performance of anaerobic digestion in categories such as marine eutrophication and terrestrial ecotoxicity is worse than in landfills [31] As a result of analysis with the LCA program, incineration outperformed landfill in terms of environmental impacts [32]. Anaerobic digestion detects more environmentally friendly. Scenarios 1 and 2 were found to have very close global warning potential. Scenario 2 found the least environmental impact in terms of the human toxicity potential of the waste management system. The impact of human toxicity includes global effects arising from global warming, regional consequences related to human toxicity, as well as local effects such as the creation of photochemical oxidation and urban air pollution. S3 also provides much better results for acidification and freshwater eutrophication. However, marine eutrophication potential seems much less in S2.

CONCLUSION

Waste management is an important issue that is considered one of the biggest problems in today's developed cities. As well as neutralizing the wastes collected from the urban environment by processing them with appropriate methods, obtaining a certain amount of environmental gain from these wastes is an approach that has been increasing in importance and application recently. In addition to saving energy and materials by recycling recyclable wastes, organic wastes are also processed to support energy production through biogas production. Incineration and anaerobic digestion methods are the two most preferred methods for energy production and serious energy gains can be achieved if these methods are used as integrated. In addition, as a result of the effective implementation of recycling processes, it is possible to obtain a negative effect in value but a positive effect in meaning. Anaerobic digestion can help to reduce greenhouse gas emissions by capturing and utilizing methane that would otherwise be released into the atmosphere during the decomposition of organic waste in landfills. On the other hand, an interpretation is needed from the perspective of LCA to calculate the holistic effects of these disposal methods. Thus, a full assessment of the environmental effects of the energy consumed during the treatment of wastes and the energy obtained as a result of the treatment of wastes will be made. In these processes, energy is not the only input and output, but different indirect components are also considered as input and output. In this study, four different waste management processes, namely landfill, incineration, anaerobic digestion, and recycling, were evaluated in different scenarios from the perspective of LCA. The results show that while landfill is the method with the highest environmental burden, great reductions in environmental impact occur with the implementation of incineration and anaerobic digestion processes. Since these two processes also provide energy production, a decrease in negative effects during the process has been observed. The recycling process, on the other hand, enabled environmental gains by making environmental impacts positive. As presented in Table 3, especially the recycling of plastics and metals is considered the process that reduces the burden on the environment the most. According to the values shown in Table 2, S1, S2, and S3 produced emissions of 3233.1, 328.8, and -848.9 kg of CO_2eq, respectively, and according to this data, recycling has a positive effect on the global warming potential by reducing the impact. According to the results, a combination of methods consisting of processing the organic components of urban wastes through anaerobic digestion and using the obtained biogas in energy production, recycling the recyclable wastes and generating energy by incinerating the remaining combustible wastes is suggested as the most environmentally friendly method. There is no other option but to send non-recyclable and non-incinerator wastes to a landfill, but in this case, the negative effects of a landfill will be minimized. This study aims to assess the environmental impact of different waste management options, helping decision-makers make informed choices about how to manage the MSW in a way that minimizes environmental damage. By adopting a hierarchical waste management system, prioritizing waste reduction, recycling and responsible waste-to-energy conversion, the environmental footprint of MSW can be significantly reduced. By implementing recommended measures and encouraging collaboration among stakeholders, we can turn MSW into a resource rather than a burden.

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.

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Not declared.

ETHICS

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

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Research Article

Study on defluoridation of water by using activated carbon derived from chestnut shell as adsorbent

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ABSTRACT

The present work intended to produce new cost-effective alkali-activated adsorbents from chestnut shells with the purpose of removing fluoride from water, and to explore the effect of pyrolysis temperature on fluoride decontamination at different operational and environmental parameters. The microstructure and morphological characteristics of the resulting activated carbons were thoroughly investigated using BET, FTIR, XRD and SEM. The effectiveness of the prepared adsorbent materials in treating and remediating fluorinated water was evaluated. The impacts of several factors, including the dose of the adsorbent, the initial contamination level of fluoride, and pH on the fluoride removal efficiency were investigated. In accordance with the data, the highest adsorption was found to be at a 6 pH during 5 hours of processing duration and 0.5 g/L of dosage of adsorbent. The experimental results were well-fit by the Freundlich isotherm model and the pseudo-second-order kinetic model. The highest fluoride removal efficiency was found to be 78% at adsorption medium pH 6 and initial fluoride concentration of 10 mg/L by the adsorbent prepared at 800°C. Additional research on adsorption along with rejuvenation revealed that the reduction in adsorption potential to 10% following four repetitions of operation involving regeneration, thereby showcasing the adsorbent's versatile applicability for repeated use.

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INTRODUCTION

The occurrence of fluoride within water supplies is currently identified as one among the most serious worldwide water-related concerns, making the development of efficient technology for eliminating it a crucial concern for enhancing the well-being of humans in afflicted regions. Adsorption has risen to prominence as a popular method for removing fluoride from water, and it has garnered a lot of interest in recent years due to the fact that it is an effective, economical remediation method along with its easiness to apply. Although fluoride can help people to strengthen the ortho skeletal and dental structures when consumed in appropriate amounts, too much consumption of it can have serious negative effects on the well-being of people [1, 2]. Particularly, ample proportions of fluoride have associated with a variety of medical challenges, including tooth and bone fluorosis, malignancy, osteoporosis, arthropathy, cerebral and mental disorders and other neurological ailments [1, 3–6]. The poisoning of waterways with fluoride influences a great number of nations all over the world; nevertheless, the most serious issues have been identified in Tanzania, Bangladesh, Pakistan, India and Ghana [7–9]. In all, around 200 million individuals in 28 nations have been adversely impacted, this issue being especially severe in some of those nations [10, 11]. In Tanzania, 30% of the drinkable water had fluoride concentration more

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than 1.5 mg/L [12, 13]. There should be no more than 1.5 mg of fluoride per litre in water used for drinking, according to guidelines established by the World Health Organization including the European Commission (EC Directive 98/83/EC) [14]. In India, the concentration of fluoride in water is contingent upon geological factors and ranges from 0.5 to 48 mg/L as the naturally existing fluoride content in water, varying due to different geological parameters. In India, 19 states exhibit high fluoride levels in groundwater, surpassing 40 mg/L. In Churu (RJ) the fluoride level in ground water is determined to be 30 mg/L, while in Nagaur (RJ) it is round 44 mg/L. The states with F^- levels surpasses the WHO guidelines include Uttar Pradesh, Gujarat, Rajasthan, Madhya Pradesh, Haryana, West Bengal, Andhra Pradesh, Telangana, Maharashtra, Punjab, Karnataka, Tamil Nadu, and others [4]. It is believed that the efficient elimination of fluoridated water is a challenging and inspiring topic, particularly in the above locations.

Many fluoride removing strategies, including membrane separation [15, 16], ion-exchange [17], coagulation [18], precipitation [19, 20] and adsorption [21] are currently implemented and used. Despite their usefulness, several of these techniques have limitations. In particular, ion exchange isn't the most successful or cost-efficient approach because of the expense of the resin and relatively limited selectivity, along with the fact that it has to be constantly regenerated [22]. The usage of membranes comes with its own set of problems such as the expensive nature of the membranes themselves, high expense of cleaning and controlling fouling [4, 23]. This makes the procedure rather costly to operate [24, 25]. Alternately, coagulation has its drawbacks despite being a cheap method since it requires large dosages, which leaves behind significant leftover quantities of aluminium [22]. On the contrary, it has been claimed that the precipitation technique may be used towards the fluoride removal. This approach is particularly effective when calcium, aluminium, or ferrous salts are used; however, the poor solubility of these produced compounds restricts the potential for fluoride removal [22, 26]. Because of the above reasons, adsorption has been proved to be the best way to get elimination of fluoride because it has several benefits compared to alternatives [26–28]. In particular adsorption is the best approach as it is inexpensive, easy to use, more selective, and readiness of adsorbent.

There are many different types of adsorbents that have been utilized [15, 23, 26, 29]. These include expensive materials like ion exchange resins [30], activated carbon (AC) [31–33], more affordable ones like carbon nanotube fibers [34, 35], bone charcoal [36], fly ash [37] and clay [38] etc. Among such options, activated carbon appears to be proven most useful due to its most of the beneficial properties. These include a wide specific area for adsorption, great porosity and elevated catalytic efficiency [39, 40]. Activated carbon does have certain benefits, but it is not very effective at removing inorganic contaminants like fluoride due to its limited sorption capability and lack of selective ability. In recent times, a significant number of authors have included in their work about the transformation of activated carbon materials using a variety of chemicals with an effort to circumvent this constraint.

In order to improve activated carbon's efficiency towards the defluoridation, it has lately been processed using silicates [41, 42], magnesium oxide [43], lanthanum oxide [44, 45] and aluminium oxide [46]. In aforementioned substances, lanthanum shows the greatest promise; however, lanthanum oxide is quite pricey, consequently it might be more practical to combine lanthanum oxide using less pricey metallic substances (such as magnesium, silicon, calcium, etc.) on activated carbon for generating mixed metal based modified activated adsorbents having a significant ability for adsorption [47]. However, magnesium modified adsorbents are recommended since they are cheap and show excellent adsorption ability towards defluoridation throughout a broad range of pH (i.e. 2–10) [18, 48]. For the elimination of arsenate and fluoride, magnesium (Mg) has been shown to combine using lanthanum on hydrotalcite in earlier researches [49]. However, such compounds are no longer used because of the high price of unadulterated magnesium salts used primary reagents [50]. Despite magnesium oxide has lower cost and impressive fluoride adsorption capabilities [51], its fine particle size enhance the surface area and could boost the fluoride removal ability [52]. Due to this, adding magnesium to modify the activated carbon could boost overall stability besides maximizing overall advantages of it.

Based on the aforementioned information, chestnut shell adsorbent (CSAC) was developed. The material's efficacy towards defluoridation was tested in batch studies. Within the context of this research, it has been investigated the defluoridation capacities of activated carbon produced from chestnut shells. This study involved an exploration of the influence of many factors, including water pH, initial content of fluoride and adsorbent dosage. Whereas scanning electron microscopy (SEM), Fourier transform infrared spectroscopy (FTIR) and X-ray diffraction (XRD) were used to examine the morphological and structural characteristics of the activated carbon. The adsorption mechanism was also described using kinetic and isotherm models.

MATERIALS AND METHODS

Materials

Analytical-grade reagents were utilized throughout the experimentation. The fluoridated water mixture was prepared by using anhydrous sodium fluoride (NaF) supplied by Merck. A standard sample solution calibrated to a proportion of 1000 mg/L had been obtained by mixing 2.210 grams of sodium fluoride with 1000 ml of distilled water. Then the original solution was diluted in order to produce the solutions having appropriate level of fluoride content.

Preparation of Activated Carbon

The research found that activated carbon synthesized from chestnut shells required impregnations to be effective and it was done following by the procedures reported in the literature [18]. The chestnut shells were cleaned by distilled water for the elimination of adhering debris and other unwanted materials attached to them before being dried overnight approximately at 100°C to minimize moistness percentage [53]. The dehydrated product was crushed and screened until its particulate diameter was uniformly about 0.45–0.15 mm. The chestnut shell material that was prepared was designated as CS. Then it was kept at ambient temperature for 24 hours, 20 g of dried chestnut shells was soaked using 250 ml of the potassium hydroxide (2 M), which was used as the activating agent. After filtering, the material had been placed into furnace. The activation of the precursor was done by using pyrolyzer; carbonization was undertaken at 600°C, 700°C and 800°C and was maintained for 2 hours during entire process, with a consistent heating flow of 99% purity of nitrogen gas supply. Following, cooled carbonized residues have been cleaned using milli-Q distilled water until neutral pH, while the pH 7 was maintained consistent (using HP pH meter, model CRISON 602) [53, 54]. The resulting activated material, after carbonization, was subsequently heated in an oven for drying at a temperature of 100°C for 24 hours so as to get the final activated carbon products (CSAC600, CSAC700 and CSAC800).

Analytical Determinations/ Quantitative Findings

The SPADNS spectroscopic approach [50] was used to determine the fluoride residual content. This technique involves the interaction among F^- ions with Zirconium, which separates a portion of F^- ion form a colorless (ZrF_6^{2-}) anionic compound as well as colored agent. When comparing with conventional fluoridated sample, the color generated gets gradually lighter on increasing the quantity of fluoride. The Zirconium-SPADNS complex combined compound was employed because of its high stability when exposed to the dark and its ease of preparation by combining two distinct chemicals/reagents [50]:

- Reagent 1 was prepared by combining 958 mg of SPADNS (2-(4-Sulfophenylazo)-1, 8-dihydroxy-3, 6-naphthalene disulfonic acid trisodium salt) with 500 ml of distilled water. The SPANDS was supplied by Sigma Aldrich.
- Reagent 2 was prepared by mixing 133 mg of Zirconyl chloride hydrate with 25 ml of distilled water. Then the 350 ml of hydrochloric acid (HCl) was added to the above and additional distilled water was also added to make a total volume of 500 ml solution. The Zirconyl chloride hydrate was supplied by Sigma Aldrich and HCl was supplied by CDH.
- Reagent 3 (Zr-SPADNS), a complex mixture, was prepared by combining equal volumes of reagent 1 and reagent 2. The mixture was stored in a dark environment as it can remain stable for approximately 2 years in the dark environment.

After that, 2 ml of Zr-SPADNS solution was poured into ten milliliters of deionized water, which serves as blank, and subsequently into ten milliliters of specimens that have been diluted with water. The mixture has been thoroughly combined after each addition.

Characterization Approaches

Activated carbon material had been examined regarding their surfaces morphological structures utilizing Scanning Electron Microscope (Jeol JSM-6390 LV) alongside energy dispersive X-ray system (EDS). Following standard experimental conditions, the crystallographic structure was determined by X-ray diffraction (XRD) (Bruker D8 FOCUS). For the study of the chemistry of bonds on chestnut shell was analyzed by Fourier Transform Infrared Spectroscopy (FT-IR) (Perkin Elmer). At a temperature of 77 K, the Brunauer, Emmett, and Teller (BET) analytical program was utilized to figure out the specific surface area. The adsorbent was analyzed both proximally and ultimately. The proximate analysis comprised the percentage of moisture, volatile matter, carbon content matter and leftover non combustible residue in the form of ash. The ultimate Analysis of elements in biochar samples was performed using CHNSO Elemental Analyzer.

Adsorption Studies

Fluoridated samples in beakers have been subjected to adsorption studies with varying proportions of adsorbent added under steady temperature. The substance was stirred using magnetic stirrer at a steady rate of 80 revolutions per minute (rpm). Throughout the course of the examinations, a variety of experimentation process parameters, including pH (ranging from 3 to 9), commencing concentration of fluoride (ranging from 2 to 10 mg/L), adsorbent dosage (ranging from 0.1 to 1.0 g/L) and contact duration (24 hours for kinetics and equilibrium), were individually and separately altered as the ranges of parameters were chosen based on the literature [27, 55]. Adsorbate was removed from examined specimens of water by passing them through filter papers with a pore diameter of 45 µm, whereas the fluoride leftover level was one of many characteristics measured within the resulting filtrate. The average of 3 replicated and separate investigations are resulted in these findings. Eq. (1) was used to figure out the proportion of fluoride that was removed (%R).

$$\text{Removal (\%)} = \left(\frac{C_0 - C_f}{C_0}\right) \times 100 \tag{1}$$

Where C_0 represents the fluoride level of pre treated water sample (mg/L), and C_f represents the fluoride content after adsorption (mg/L).

Below Eq. (2), was used to figure out the adsorption capability Q_e (mg/g) of the sorbent.

$$Q_e = \left(\frac{C_0 - C_e}{m}\right) \times V \tag{2}$$

Where C_e (mg/L) represents the level of fluoride after treatment, V (L) corresponds to the volume of the untreated sample, while m (g) depicts the adsorbent dosage mass that is being utilized.

Equilibrium Experiments

All isothermal tests were conducted by adding a constant dosage of adsorbent (g) to 200 mL contaminated sample with fluoride level (2–10 mg/L) in 250 ml beakers. The findings of the experiments were analyzed by using the Langmuir, Freundlich and Temkin isotherm models respectively to account for the data on adsorption. The equation for the Langmuir model is represented by Eq. (3). The Langmuir model establishes a correlation between the fluoride level of the liquid after the equilibrium and the uptakes of the solid phase adsorbate (Qe).

$$Q_e = \frac{Q_m K_L C_e}{1+K_L C_e} \quad (3)$$

Where Q_m (mg/g) is the theoretically calculated monolayer/maximal adsorption rate, while K_L (L/mg) corresponds to the energy of fluoride sorption.

According to the model developed by Langmuir, the adsorbent is assumed to have a finite adsorption potential (Q_m) and the adsorbate develops a monolayer over the exterior of the adsorbent, while no or little interactions exists among the deposited contaminants.

The Freundlich model relates equilibrium amounts of fluoride (mg/L) to adsorption capabilities of Q_e (mg/g) of adsorbent which may be stated as Eq. (4):

$$Q_e = K_f C_e^{\frac{1}{n}} \quad (4)$$

Where K_f is a constant associated with adsorption efficiency and 1/n represents another constant parameter associated with the amount of adsorption intensity that takes place or the heterogeneousness of surface, values of 1/n >1 suggest cooperative adsorption, whereas 1/n=0 denotes a heterogeneous phase and 1/n <1 then the Freundlich isotherm is normal.

The Temkin isotherm equation corresponds to a three factor model represented as Eq. (5) that has been employed to match the observational data.

$$Q_e = \frac{RT}{B_t} \ln (a_t C_e) \quad (5)$$

Where Q_e (mg/g) represents the equilibrium adsorbed quantity, C_e (mg/L) is the adsorbate equilibrium quantity, and a_t denotes the variability coefficient, which ranges from 0 to 1. This formula is applicable across a wide range of concentrations in a solution; while it fails to comply with Henry's rule for low levels because it adequately changes to a Freundlich isotherm, it does anticipate a monolayer adsorbance of the Langmuir isotherm for elevated concentrations.

Kinetics Studies

The pseudo-first-order (PFO) and pseudo-second-order (PSO) kinetics for adsorption of ions of fluoride have been explored, and appropriate resulting adsorption kinetic parameters were then subsequently evaluated to quantify the sorption rates and further found the appropriate expression rates indicative of potential interaction mechanisms. The pseudo-first-order and pseudo-second-order approaches utilized during the data assessment have been depicted in Eq. (6) and Eq. (7):

$$Q_t = Q_e\left(1- e^{-k1t}\right) \quad (6)$$

$$Q_t = \frac{k_2 Q_e^2 t}{1+k_2 Q_e t} \quad (7)$$

Where, the adsorbed quantity of fluoride after equilibrium time t (minutes) is denoted by Q_t and Q_e (mg/g). The pseudo-first-order rate constant, k_1 is denoted in units as L/min; the pseudo-second-order rate constant, k_2 is written in units as g/mg/min; while t, in minutes represents the overall interaction duration.

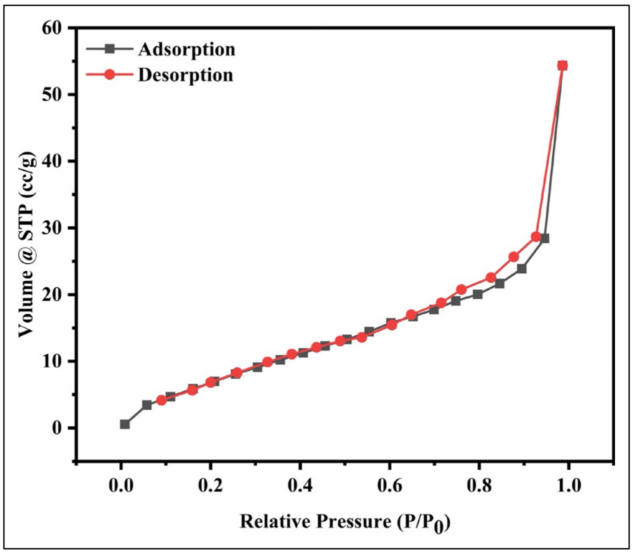

Figure 1. Nitrogen adsorption-desorption isotherms of CSAC800.

RESULTS AND DISCUSSION

Analysis of Activated Carbon

BET Analysis

The experimental outcomes revealed that the CS surface exhibited mesoporous surface appearance, featuring multiple pores and an irregular, block-shaped configuration. In comparison, CSC800 exhibited a surface that was noticeably rough and contained a large number of pores. The presence of these pores was a direct result of the volatiles emission during pyrolysis. The CSAC800 surface displayed a broken and irregular texture, characterized by the presence of multiple well-defined pore structures. The interaction between KOH and the biomass led to a significant reduction in the pore size of CSAC800. This interaction stimulated the production of small molecular gaseous substances (H_2, CO and CO_2). Cations of alkali metals produced have the ability to insert themselves into the partially formed char material, which enhances the breakdown and fragmentation of the biochar [56]. The findings clearly elucidate that the transformative impact of pyrolysis pretreatment with KOH wielded a profound influence on the captivating morphology of biochar, resulted in notable alterations in its morphology.

The adsorption isotherms of three specific variants CSAC600, CSAC700, and CSAC800 displayed Type IV isotherm as represented in Figure 1 providing confirmation of the presence of macropores [57] and in conjunction exhibiting an h4 hysteresis indicating mesoporous arrangements or configurations that were created upon the outermost layer of biochar derived from chestnut shells that were activated using KOH [58]. The range of pore diameters found in CSAC600, CSAC700, and CSAC800 spanned ranging between 2 to 50 nm, thereby ensuring the adsorbent's mesoporous characteristics. The measured values for CSAC800 included a specific surface area (SSA) of 912.38 m^2/g, pore volume of 0.188 cm^3/g and pore diameter of 11.131 nm as detailed in Table 1. Compared to CS, notable enhancements

Table 1. The specific surface area (SSA), pore volume, and diameter of various adsorbents were determined, utilizing parallel experimental investigations to ensure accuracy and reliability and the data are presented as the average of two specimens along with the corresponding standard deviation

Adsorbent	SSA (m^2/g)	Pore volume (cm^3/g)	Pore size (nm)
CS	3.76	0.0318	0.0293
CSC800	15.12	0.056	3.637
CSAC600	472.58	0.096	8.342
CSAC700	785.80	0.149	9.021
CSAC800	912.38	0.188	11.131
CSAC800-F^-	680.16	0.112	8.751

in specific surface areas (SSA) were observed in CSC800, CSAC600, CSAC700, and CSAC800. CSC800 exhibited a 4.02 times increase, while CSAC600, CSAC700, and CSAC800 displayed remarkable improvements of 125.68, 208.99, and 242.65 times in their respective specific surface areas. Similarly, the pore volumes of CSC800, CSAC600, CSAC700, and CSAC800 exhibited significant increments of 1.76, 3.09, 4.80, and 6.06 times respectively. The BET analysis yielded compelling evidence that the alkali-activated biochar derived from chestnut shells showcased remarkable enhancements in specific surface area and the presence of mesoporous structures. Consequently, the material exhibited a plethora of highly effective interfacial adsorption sites, offering ample opportunities for the efficient adsorption of target compound (fluoride).

FT-IR/ Functional Group Study

The FTIR spectra of CS revealed distinctive spectral features as depicted in Figure 2. The peak observed at 1460 cm^{-1} was associated with the deformation vibration of $-CH_2$ groups. Moreover, distinctive spectral peaks were discerned at 1083 cm^{-1}, 1244 cm^{-1}, 1640 cm^{-1}, 2927 cm^{-1}, and 3423 cm^{-1}, aligning with the stretching vibrations of C-O-C, C-O, C = O, C-H, and -OH groups, respectively. These observations furnish valuable knowledge about the molecular composition and structural characteristics of CS [58–60]. Nonetheless, the FTIR peak intensities observed in CSC800 and CSAC800 were markedly diminished as a consequence of the utilization of a high pyrolytic temperature. This finding aligns consistently with the outcomes of a prior investigation, reinforcing the correlation between elevated pyrolytic temperatures and reduced FTIR peak intensities [61]. As the temperature at which calcination occurs increased, the patterns observed in the spectrum parameters of the adsorbents showed stronger magnitudes for the peaks located at 1083 cm^{-1} and 1630 cm^{-1}. This phenomenon can be attributed to the activation of alkali compounds.

Importantly, the distinct spectra in the Fourier-transform infrared (FTIR) spectroscopy at 1421 cm^{-1}, which corresponds to the stretching vibration of C = C bonds, was solely detected in CSAC800. Importantly, the distinct peak

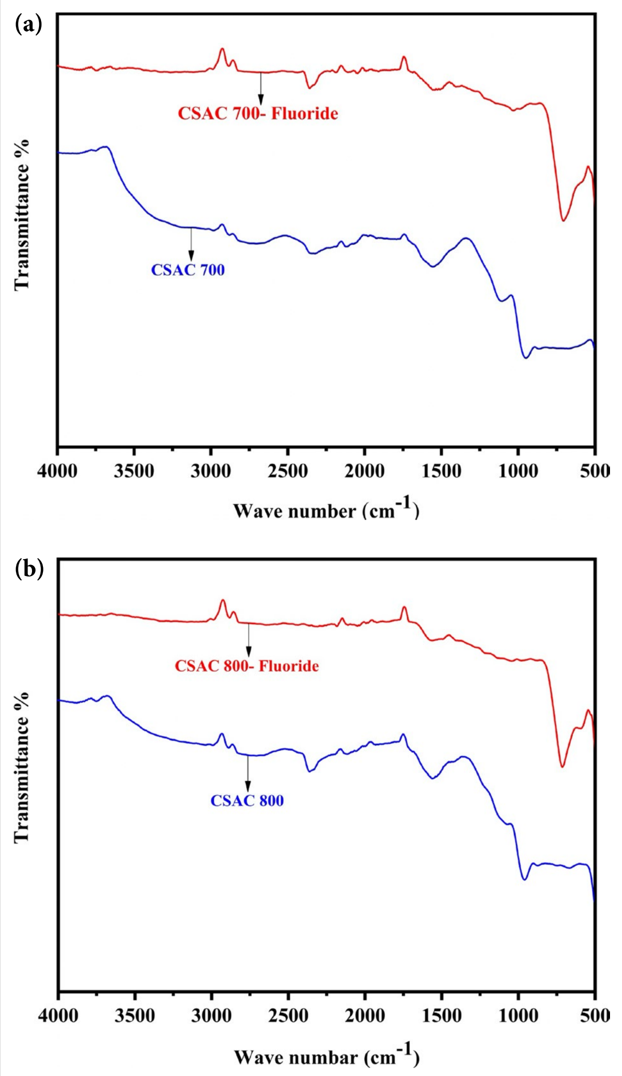

Figure 2. **(a)** FTIR spectra of activated carbons CSAC700 derived from chestnut shells. **(b)** FTIR spectra of activated carbons CSAC800 derived from chestnut shells.

in the Fourier-transform infrared (FTIR) spectroscopy at 1421 cm^{-1}, which corresponds to the stretching vibration of C = C, was solely noticeable in CSAC800. After adsorption the peak at 993 cm^{-1} shifted to 710 cm^{-1}.

Scanning Electron Microscopy (SEM)

Scanning Electron Microscopy (SEM) was employed to analyze and track the surface characteristics, texture and the micro-structural features and changes occurring in the materials. The surface-morphology of AC, which were obtained from chestnut shells are shown in Figure 3 since the aforementioned substances were shown to comprise the most effective material for adsorption throughout the studies that followed. The chestnut shell carbons exhibited a uniform and well-defined structure characterized by a prevalence of macropores, showcasing an average pore diameter of 12 μm [62]. In accordance to an investigation examining the morphology of activated carbon, it appears that the C-KOH bonding generates an extensive density of microscopic

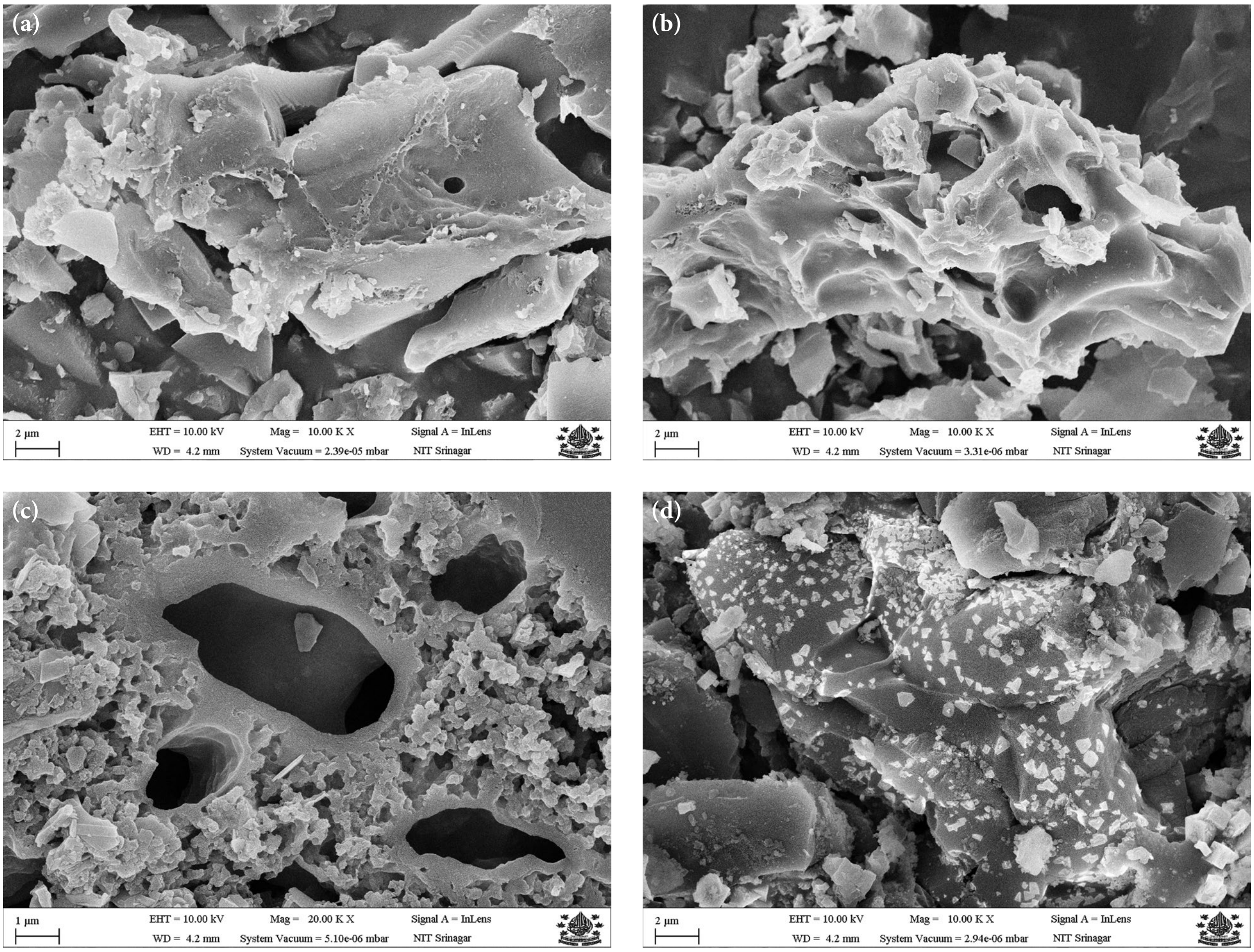

Figure 3. **(a)** SEM images of chestnut shell activated carbon CSAC700 before adsorption. **(b)** SEM images of chestnut shell activated carbon CSAC700 after adsorption. **(c)** SEM images of chestnut shell activated carbon CSAC800 before adsorption. **(d)** SEM images of chestnut shell activated carbon CSAC800 after adsorption.

pores, which substantially boosts the overall surface vicinity and capacity among those pores [63]. Additionally, the pore spaces within activated carbon exhibit irregular configurations that might serve as adhering surfaces for adsorption agents of varying dimensions. The adsorbent produced during the present investigation might come in a range of forms, including those with varying porosity, wall dimensions and patterns as shown in Figure 3. The activation procedure resulted in considerable removal of organic matter and subsequent porosity formation. Figure 3 also displays the SEM images comprising the CSAC700, and CSAC800.

The visualizations reveal cavernous cavities running across every specimen, which is suggestive regarding spontaneous activation-induced gasification for volatile materials. These AC specimens had been entirely composed by accumulated high-quality particulates, implying that it might be crucial for adsorption towards fluoride ions within various contaminated solutions. As was already mentioned, the disintegration of carbonates formed while the calcining operation is what is responsible for those morphological alterations. From Figure 3b, one can easily observe a uniform dispersion of fluoride adsorption throughout its entire area following fluoride adsorption. Additionally, respective SEM representations appeared after fluoride adsorption across the exteriors of competing adsorbent elements, in addition to the above it is clear that the CSAC's interface has adsorbed a higher proportion of fluoride from solution.

XRD Analysis

The X-ray diffraction (XRD) peaks detected at 2θ = 14°, 20° and 39° can be correlated to the presence of the non-crystalline carbon (002) structure and graphitic carbon lattice planes (100) respectively according to Figure 4. Distinctive prominent XRD peaks corresponding to the crystallographic appearance of cellulose in CSAC were identified at angles of 16.06°, 21.82°, and 34.56°, which revealed that cellulose, had completely decomposed [64]. The disappearance of a distinct dispersion pattern at 30.16° indicates that there are no metallic inclusions embedded over the activated carbon's surface. Additionally, the relatively low intensity of the peak in activated carbon pointed to the fact that majority of the chestnut shell underwent decomposition to a state of carbon lacking crystalline structure throughout the process of alkali-activated pyrolysis. The existence of a carbon structure characterized by amorphous or disordered properties promoted the availability of additional adsorption sites to enhanced adsorption capacity.

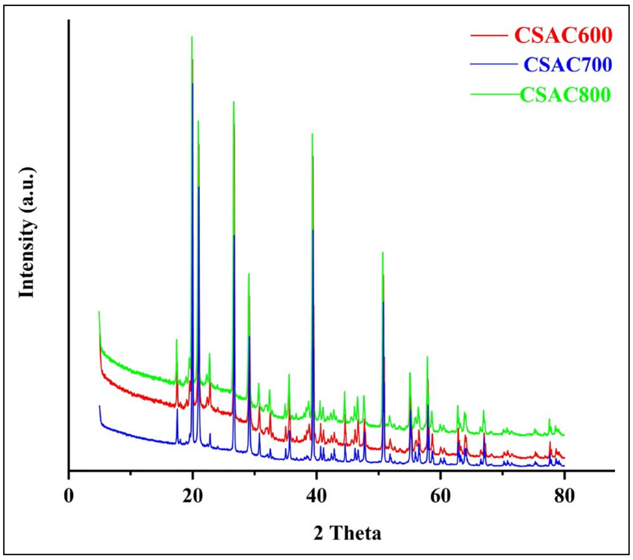

Figure 4. XRD profiles of activated carbons derived from chestnut shell.

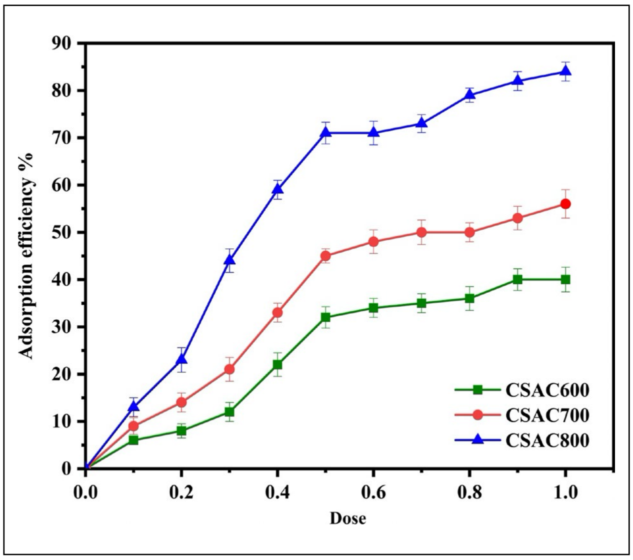

Figure 5. Effect of adsorbent dose on F^- adsorption (Ci 10 mg/L, pH 7.0±0.1, time= 24 h, T= 25±1 °C).

Batch Adsorption Experiment

Effect of the Dosage/ Impact of Adsorbent Dosage Along with Adsorbent Comparison

Following the qualitative detection of fluoride adsorption on chestnut activated carbon, various quantitative examinations were conducted. In a series of batch experiments, the impact of varying dosage of activated carbon adsorbent was investigated and studied to understand how the adsorbent's quantity influences its capability to mitigate the fluoride contamination in the solution and to assess its potential for removing fluoride ions (F^-) effectively. The optimal adsorbent quantity was obtained by altering the adsorbent dosage falling between 0.1 to 1.0 g/L, while maintaining the constancy of all other factors. The efficacy of the removal, in relation to both the remaining fluoride concentration and associated percentages, is graphically represented in Figure 5. To evaluate the influence of varying adsorbent levels, 25 ml of adsorbate mixture containing 10 mg/L had been taken around 7 pH. The resulting mixture was then equilibrated using 0.1 to 1.0 g of CSAC over 24 hours.

From Figure 5, it is evident that as the quantity of sorbent employed went up from 0.1 to 1.0 g/L; there was a corresponding increase in the adsorption capacity. Because there were more active spots available, it became apparent that fluoride adsorption enhanced when CSAC dosage rose. Alterations within elimination process could possibly be attributed to the initial contaminant level, during which each adsorbent spot remained unoccupied. As illustrated, upon elevating the adsorbent quantity, the elimination percentage of fluoride surged to 78% at a 6 pH for the CSAC800 adsorbent. This led to a left-behind level of fluoride falling to 2.2 mg/L, accomplished by employing under 0.5 g/L of the specified adsorbent. For the correlation, an adsorbent named CSC800 was meticulously formulated and the adsorption efficiency by CSC800 was around 20%. This showed that the activation agent had a greater impact on

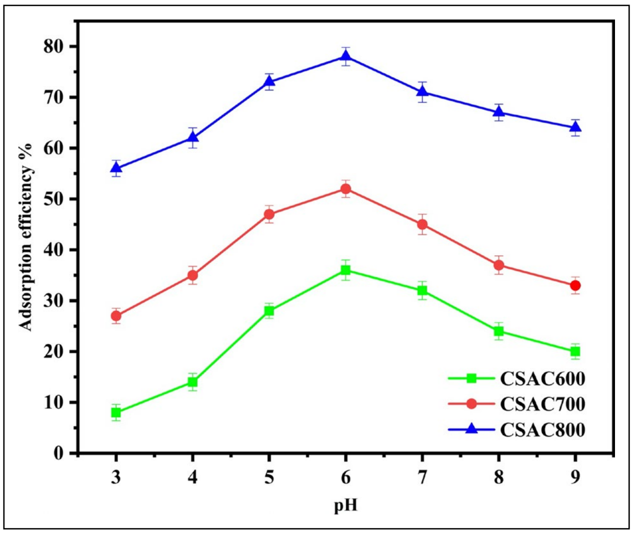

Figure 6. Effect of pH on F^- adsorption (Ci 10 mg/L, dosage 0.5 g/L, time 24 h, T=25±1 °C).

the adsorption process. Yet, when the quantity of sorbent used exceeds beyond 0.5 g/L, the active sites of adsorbent reached their limit, resulting in a substantial decrease in the fluoride concentration left in the solution, which in turn weakened the effectiveness of the adsorption process. To account for both the amount used and the remaining concentration, a dosage of 0.5 g/L for CSAC800 was chosen for subsequent experiments.

Effect of the Initial pH

The pH level of solution had a notable influence on the characteristics of the adsorbent's surface. The impact of pH on the adsorption of fluoride onto chestnut activated carbons was examined by altering the solution's pH within the range of 3 to 9. These tests were conducted with exposure time of 24 hours, at 25°C, and a dosage of 0.5 g/L. The findings from these experiments are presented

Table 2. Evaluating the adsorptive capabilities of CSAC800 comparative to several adsorbents documented in published works for defluoridation

Adsorbent	Initial concentration mg/L	Adsorbent dose	pH	Temp. °C	Equilibrium time (min.)	Surface area m^2/g	Applicable isotherm models	Adsorption capacity/ efficiency	Ref.
γ-Al_2O_3 hollow tubular alumina	100	50 mg/L	3	30	1440 min.	306.14 m^2/g	Freundlich	84.25 mg/g 75%	[69]
Sawdust impregnated ferric hydroxide and activated alumina	5–50	0.1 g/10ml	6.5	30	240 min.	22.5 m^2/g	Freundlich	2.42 mg/g 74%	[70]
Activated alumina	5 mg/L	0.4 g/L	6–8	25	1440 min.	198 m^2/g	_	35 mg/g 69%	[71]
Hydroxyl aluminum oxalate (HAO)	10 mg/L	1 g/L	6.5	24	239 min.	68.34 m^2/g	Langmuir	400 mg/g 75.9%	[72]
Zirconium phosphate	1–10	2 g/L	2–12	30	60 min.	129 m^2/g	Langmuir	4.268 mg/g 76%	[73]
Lanthanum-modified pomelo peel biochar	10 mg/L	1.0 g/L	5.2	25	1440 min.	506.30 m^2/g	Freundlich	7.62 mg/g 82%	[74]
Crushed oyster shells modified AC	10 mg/L	20 g/L	7±0.1	30	1440 min.	_	Freundlich	1.5 mg/g 76%	[75]
Mytilus coruscus shells	50 mg/L	3.33 g/L	5	25	360 min.	4.363 m^2/g	Langmuir	82.93 mg/g 56.9%	[76]
Magnesium modified coconut shell	10 mg/L	0.2 g/L	8	25	240	680.16 m^2/g	Langmuir-Freundlich	36.56 mg/g 16%	[50]
Activated carbon derived from chestnut shell	10	0.5	6	25	300	912.38 m^2/g	Freundlich	60.058 mg/g 78%	This study

in Figure 6. Within the pH range under examination, the adsorbent's ability to adsorb fluoride decreased with raising the solution's pH. Specifically, the increased adsorption capacity in acidic conditions can likely be associated with the existence of protonated hydroxyl groups. These groups have the potential to capture fluoride through a robust electrostatic attraction, leading to the formation of HF (hydrofluoric acid). At lower pH levels, the oxygen atoms present on the CSAC800 surface became protonated, leading to the formation of hydroxyl groups. Elevated amounts of hydronium ions under reduced pH likely undergo protonation in the CSAC's fundamental operation, allowing them to effectively adhere F^- ions. The interaction between hydroxyl groups and fluoride through ion exchange results in a significant uptake of fluoride [45, 65–67]. Such protonated functions are capable of attracting moisturized fluoride ions. Additional H_3O^+ F^- ion pairings may permeate the adsorbent pore surface, and F^- may also get swapped for protonated functions across the gaps. Conversely, because of fluorine's robust electronegativity, it can potentially be held in place through hydrogen bonding on the CSAC800 surface. However, this impact weakened when the pH level rose. As the pH level kept going up, CSAC800's capability to grab onto fluoride decreased quickly. As a result, a substantial percentage of the hydroxyl radicals within the solution engaged in a competitive interaction with fluoride during adsorption process. The results indicated that as the pH increased, the adsorption efficiency declined from 78% to 64% at pH range of 6 to 9. Less protonated surface spots might be accessible therefore fluoride wouldn't have been effectively eliminated when pH rose. So, it has been proposed that less adsorbate is removed throughout elevated pH environments because the anionic surface character of CSAC attracts F^- ions by electrostatically.

The literature-reported effectiveness of several adsorbents for fluoride decontamination is compared and presented in Table 2. Furthermore, CSAC800 adsorption capability was superior to other adsorbents mentioned in existing research. Yet, reaching a conclusive judgment on the effectiveness of the adsorbents proves challenging since the uptake efficiencies have been reported at various parameters. Comparing the economic viability of the material with biochars reported in the literature is additionally challenging due to variations in removal capabilities, characteristics, uses, and processing environments. Regarding softer materials, the most effective combinations were lower temperatures along with lengthy contact durations. Biochar is effectively recovered under lower temperatures as well as reduced heating cycles [27].

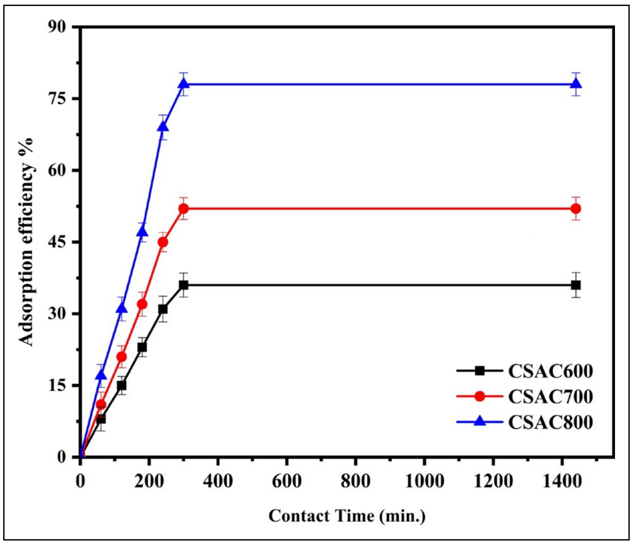

Figure 7. Effect of sorption time on F^- adsorption (Ci 10 mg/L, dosage 0.5 g/L, pH 6.0±0.1, T=25±1 °C).

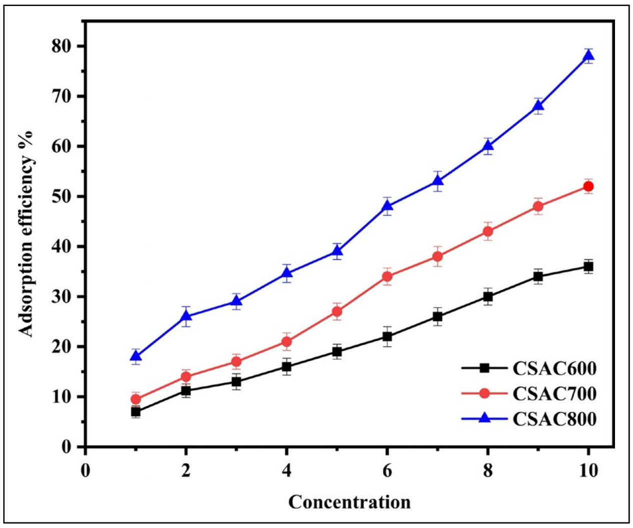

Figure 8. Effect of Ci on F^- adsorption; (Time=5 h, dosage 0.5 g/L, pH 6.0±0.1, T=25±1 °C).

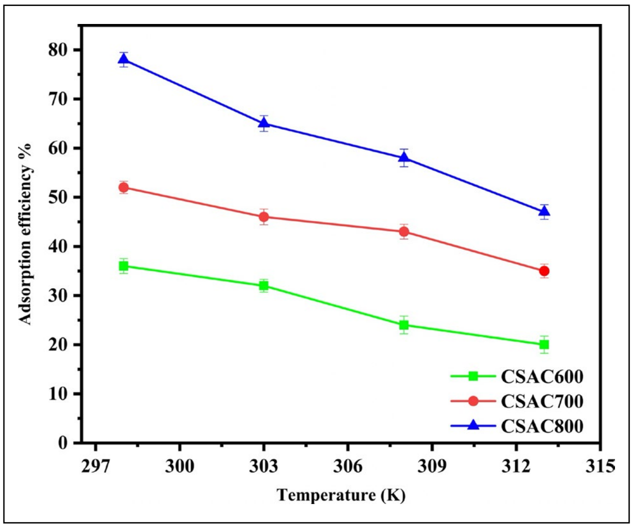

Figure 9. Effect of temperature on F^- adsorption (Ci 10 mg/L, dosage 0.5 g/L, pH 6.0±0.1, time=24 h).

Effect of Sorption Time

Another significant aspect of adsorption is how quickly the adsorbents work, so the kinetic behavior of the adsorbents represents additional important aspect for the removal mechanism; therefore, the influence of contact time has been studied and ranging from 60 to 1440 minutes (24 hours). The prolongation of the duration of the study resulted in an upward trend in the amount of fluoride that could be removed before reaching a state of equilibrium. CSAC was able to reach the steady state of sorption after 5 hours (300 minutes), and the highest fluoride adsorption effectiveness of 78% was achieved for CSAC800. The findings shown in Figure 7 revealed that once 5 hours (300 minutes) of contact time passed, there was hardly any additional improvement in fluoride removal. The fact that there exist few spots for sorption over optimum period might explain underlying cause for such phenomenon. Hence, 5 hours was chosen as the best optimal exposure period for subsequent batch experiments with chestnut shell activated carbon adsorbent materials. Importantly, this 5 hours duration proved optimal across all tested pH values.

Effect of Fluoride Concentration

Studies were conducted to determine how the adsorption was influenced by the commencing level of fluoride (2 to 10 mg/L). In this study of adsorption, overall findings that are depicted in Figure 8 pertain towards the changes that occurred in the amount of sodium fluoride that was being used. Results revealed that the degree of adsorption of fluoride varied with the level of fluoride first introduced. The study examined the impact of commencing level of fluoride (2–10 mg/L) on CSAC adsorbent (0.5 g/L) under pH 6, room temperature, along with contact period of 5 hours (Fig. 8). It was noticed that the efficiency of F^- adsorption is notably affected by the commencing level (C_i) of F^-, as shown in Figure 8. The impact of Ci was evaluated using different F^- concentrations ranging from 2 to 10 mg/L, while maintaining the other parameters like adsorbent dosage of 0.5 g/L, the exposure duration of 5 hours (300 minutes) and the pH of the solution was 6. The percentage of elimination increases as the initial F^- concentration rises. The maximal defluoridation efficacy was achieved for the adsorbent prepared at 800°C that is CSAC800. The maximal contamination elimination efficiency resulted by this adsorbent was 78%.

Effect of Temperature

The sensitivity of the adsorption process is undeniably influenced by temperature, making it a crucial aspect in the context of energy-driven mechanisms. The impact of temperature on the adsorption of fluoride ions was examined at four distinct temperatures: 298, 303, 308, and 313 K. It became apparent that as the temperature increased, the efficiency of adsorption decreased which is shown in Figure 9. This indicates the exothermic characteristic of the binding action of adsorption process. The observation had been made that adsorption progressively reduced when temperature increased, indicating an exothermic sorption mecha-

Table 3. Adsorption isotherm parameters for adsorption of fluoride on CSAC800

Isotherm model	Isotherm parameters	Temperature(K) 298K	Temperature(K) 303K	Temperature(K) 308K
Langmuir	Q_{max} (mg/g)	78.69	65.69	57.69
	K_L	3.29	3.29	3.29
	R^2	0.96	0.937	0.975
Freundlich	Q_{max} (mg/g)	60.058	52.23	43.94
	R^2	0.92	0.972	0.99
Temkin model	K_t	71.52	64.16	54.50
	R^2	0.96	0.93	0.97

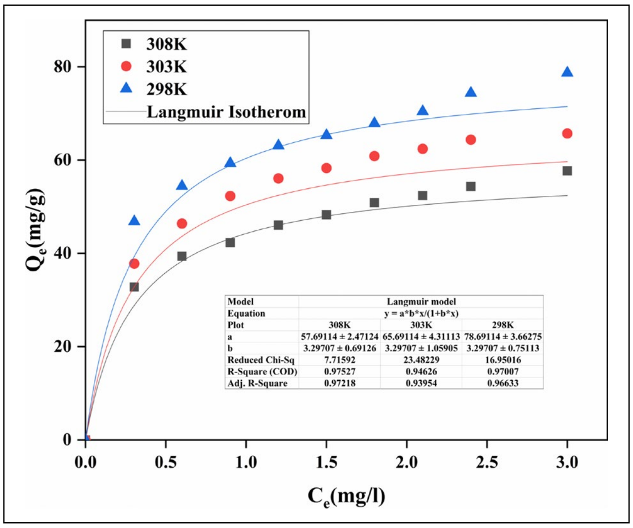

Figure 10. Langmuir isotherms describing the F- adsorption; Solution pH 6.0±0.1, dose 0.5 g/L, contact time 24 h.

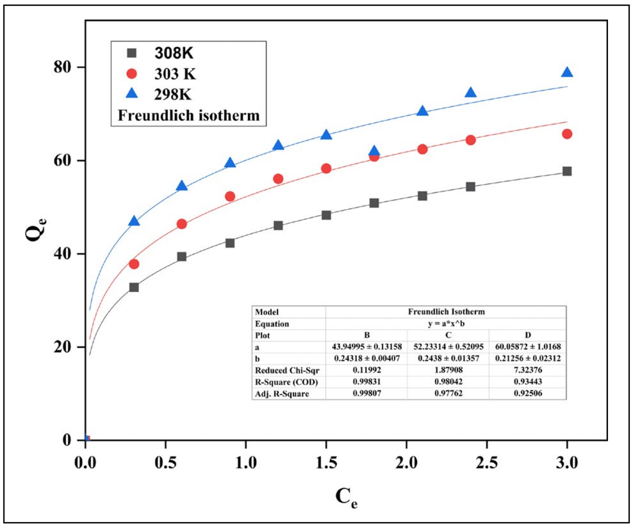

Figure 11. Freundlich isotherms describing the F- adsorption; pH 6.0±0.1, dose 0.5 g/L, contact time 24 h.

nism. The reduced adsorption could have been the consequence of the adsorbate's greater propensity to move from the adsorbent exterior into contaminated sample, which would reduce the outer layer's thickness. Subsequently, there was a notable decline in fluoride decontamination efficiency by CSAC, because of substantial reductions in both the adsorption spots along with the fluoride level.

Adsorption Isotherms

For the purpose of examining the adsorption mechanism and delineating the relationship between the amount of F^- and the adsorbent's ability to hold on to CSAC, Several mathematical models are employed. The respective parameters are displayed in Table 3. The Langmuir model posits that a constant quantity of adsorption sites is accessible on the adsorbent's surface; every spot has the capacity to accommodate only a single molecule, in other words, this refers to monolayer adsorption, where the adsorption energy does not change throughout. The dual processes of monolayer and multilayer adsorption were explained by the Freundlich model. Additionally, it clarifies that the adsorbent possesses regions with different binding strengths signifying the existence of heterogeneous regions. Study using Temkin isotherms explains how adsorption energy gets distributed throughout the adsorbent's heterogeneous regions. At low adsorbate concentrations, the model exhibits behavior similar to the Langmuir isotherm and shifts to the Freundlich isotherm characteristics when the concentrations of adsorbate are high. Figure 10, 11 and 12 displays the non-linearized representations created from the data.

According to the relative characteristics, the Langmuir isotherm model adequately explains adsorption of F^-, which also makes clear that how the adsorption potential is distributed across the adsorbent's diverse regions. CSAC800 exhibited a maximal adsorption capacity of 78.69 mg/g, while at pH 6, the maximum capacity of 60.058 mg/g was observed in Freundlich isotherm. With a relatively excellent correlation value (R^2=0.975). In accordance with the R^2 value, the Langmuir isotherm offers the most suitable fit when compared to other isotherm models.

Moreover, K_L=3.29 L/mg was the mean figures corresponding to adsorption constant (saturation coefficient) in accordance with Langmuir equation. Alternatively, the Langmuir parameter (K_L) serves as an indicator of the level of bonding between the adsorbing material and the surface. A stronger contact within the adsorbent-adsorbate is indicated by a significantly increased value of K_L, while a lower figure suggests a weaker relationship.

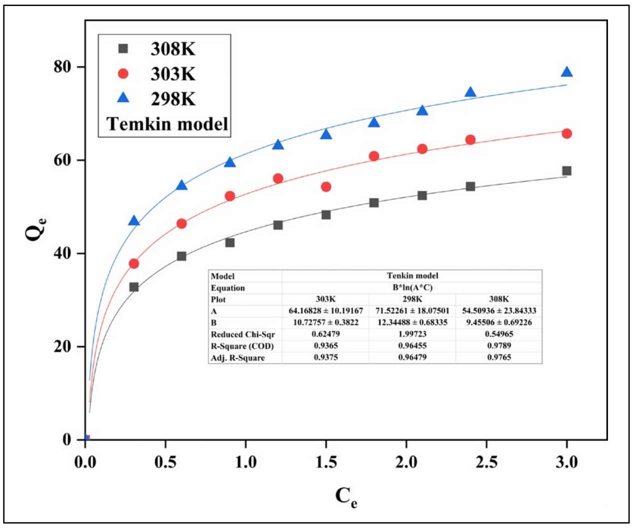

Figure 12. Temkin isotherms describing the F^- adsorption; pH 6.0±0.1, dose 0.5 g/L, contact time 24 h.

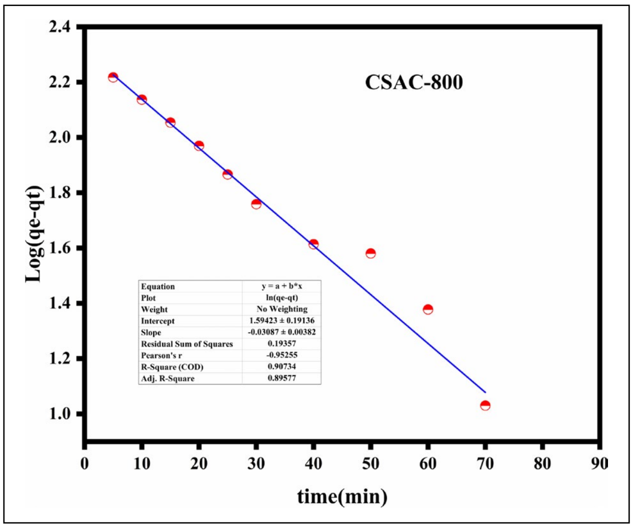

Figure 13. Kinetic PFO model for F^- adsorption; pH 6.0±0.1, dose 0.5 g/L, contact time 24 h.

In summary, the outcomes derived from employing the three-parameter equations indicated that the Langmuir represented the most appropriate fitted adsorption isotherm model and superior fit for standard equilibrium values compared with the two-parameter models.

Adsorption Kinetics and the Adsorption Mechanism for Fluoride Elimination

The adsorption kinetics of fluoride on CSAC800 were investigated under identical parameters at room temperature, specifically with a 0.5 g/L dosage of adsorbent, commencing concentration of F^- 10 mg/L, and pH 6.0±0.1. In the kinetic study, both the pseudo-first-order (PFO) and pseudo-second-order (PSO) models were employed to analyze the adsorption kinetics. The regression coefficients, rate constants (k), and equilibrium adsorption capacities (cal) for both the pseudo-first-order (PFO) and pseudo-second-order (PSO) kinetic models were determined by analyzing their corresponding linear graphs of log (q_e - q_t) against time (t) in Figure 13 and t/qt against time (t) in Figure 14.

By examining the resulting R^2 values of 0.902 for the PFO model and 0.997 for the PSO model, for CSAC800, at pH 6.0±0.1 as a reference point, it becomes evident that the PSO model fits well and is more appropriate. The coefficient of regression in the PSO context exceeds that of PFO, and the determined equilibrium adsorption capacity (q_e) derived from the linear depiction of PSO kinetics closely aligns with the empirical qe information. However, On the other hand, there seems to be a bit of a discrepancy in the q_e Figure 13 for PFO kinetics when comparing the observed value with the one deduced through computational means. The way F^- adsorbs on CSAC800 is better suited to PSO kinetics rather than PFO kinetics. This suggests that the process of adsorption is more efficient and effective when following the PSO model. However, a comparable outcome emerges when examining the non-linear representations of PFO and PSO kinetic models. In this case as well, the regression coefficient for PSO kinetics proves to be superior

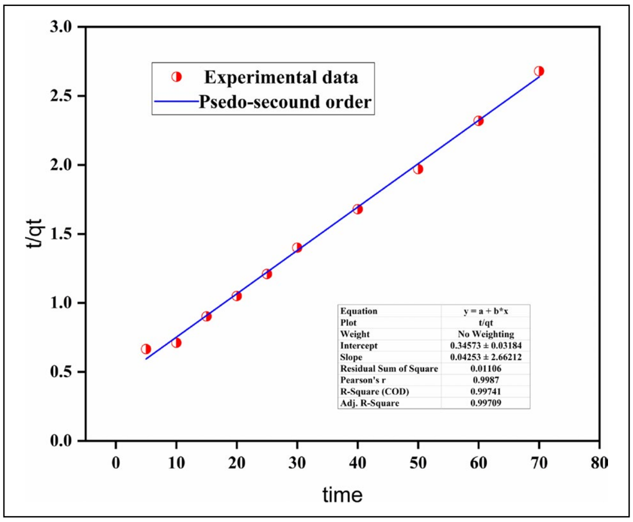

Figure 14. Kinetic PSO model for F^- adsorption; pH 6.0±0.1, dose 0.5 g/L, contact time 24 h.

to that of PFO kinetics. The computed parameters for the aforementioned models are detailed in Table 4. These findings demonstrated and validated that the chemical fluoride adsorption on CSAC800 was regulated because of electrostatic interactions followed by ion transfer [45].

Furthermore, it was evident that, the material's performance was at its maximal when the pH is set at 6. This pattern contradicts with the outcomes reported in earlier research that utilized modified adsorbents [50]. It was ascribed to the process of electrostatic interaction within the lower pH spectrum, which decreases as pH rises and results in a poor effectiveness around pH 6.

As previously determined, the process alters and ion exchange takes over at pH levels of 7 and higher. The process of fluoride removal via adsorption is intricate, encompassing diverse physical and chemical interactions between the fluoride ions and the adsorbent material. Understanding the mechanisms behind fluoride removal is crucial as it

Table 4. Kinetic parameters for PFO and PSO for adsorption of fluoride on CSAC800

Pseudo-first order	
q_e	4.92 (mg/g)
K_1	5.1×10^{-2} (g/mg min)
R^2	0.902
Pseudo-second order	
q_e	31.6 (mg/g)
K_2	4.2×10^{-2} (g/mg min)
R^2	0.997

aids in researching and enhancing the defluoridation capabilities of adsorbents. The mechanism for the elimination of fluoride by CSAC800 adsorbent is shown in Figure 15.

Thermodynamic Study

Utilizing thermodynamic analysis, the assessment of the capability and the spontaneous nature of the adsorption method was achieved by calculating three essential thermodynamic coefficients. These parameters include the free energy change (ΔG^0), entropy change (ΔS^0), and standard enthalpy change (ΔH^0). This is determined by utilizing and employing the following Van't Hoff formula:

$$K_0 = \frac{\Delta S^0}{R} - \frac{\Delta H^0}{RT} \quad (8)$$

$$K_0 = K_L \times 1000 \times \text{molecular mass of adsorbing material} \quad (9)$$

The gradient and intercept of the Van't Hoff graph, which illustrates $\ln K_0$ plotted against 1/T (Fig. 16), were employed for the determination of the thermodynamic parameters and the corresponding values are in Table 5. The reported values for ΔS^0 and ΔH^0 in removal of F^- ions are 19.59 kJ/mol/K and 8.57 kJ/mol respectively. These values imply a remarkably robust interaction and a decrease in the unpredictability of F^- ions after being adsorbed by CSAC800.

Table 5. Thermodynamic parameters for adsorption of fluoride on CSAC800

Temperature (K)	-ΔG kJ /mol	ΔH kJ /mol	ΔS kJ/ mol/K
298	2.41	8.7	19.59
303	1.441		
308	0.18		

In addition, negative reading of G^0 (ranging from 2.41 kJ/mol to 0.18 kJ/mol) at temperature fluctuation of 298K-308K indicates that overall adsorption appears both thermodynamically feasible and spontaneous. However, the diminishing negative figure of ΔG^0 at an increased temperature span indicates its decreasing spontaneity [68].

Regeneration Study/ Reusability

Regeneration studies were carried out to assess the reusability of CSAC800 in the removal of F^-. These experiments were conducted at a 7 pH, with 10 mg/L starting F^- level and 0.5 g/L as adsorbing material quantity. Following the completion of the first cycle, CSAC800 particulate matter were processed with a 0.01M NaOH solution and stirred for a period of 180 minutes, clean using deionized water imple-

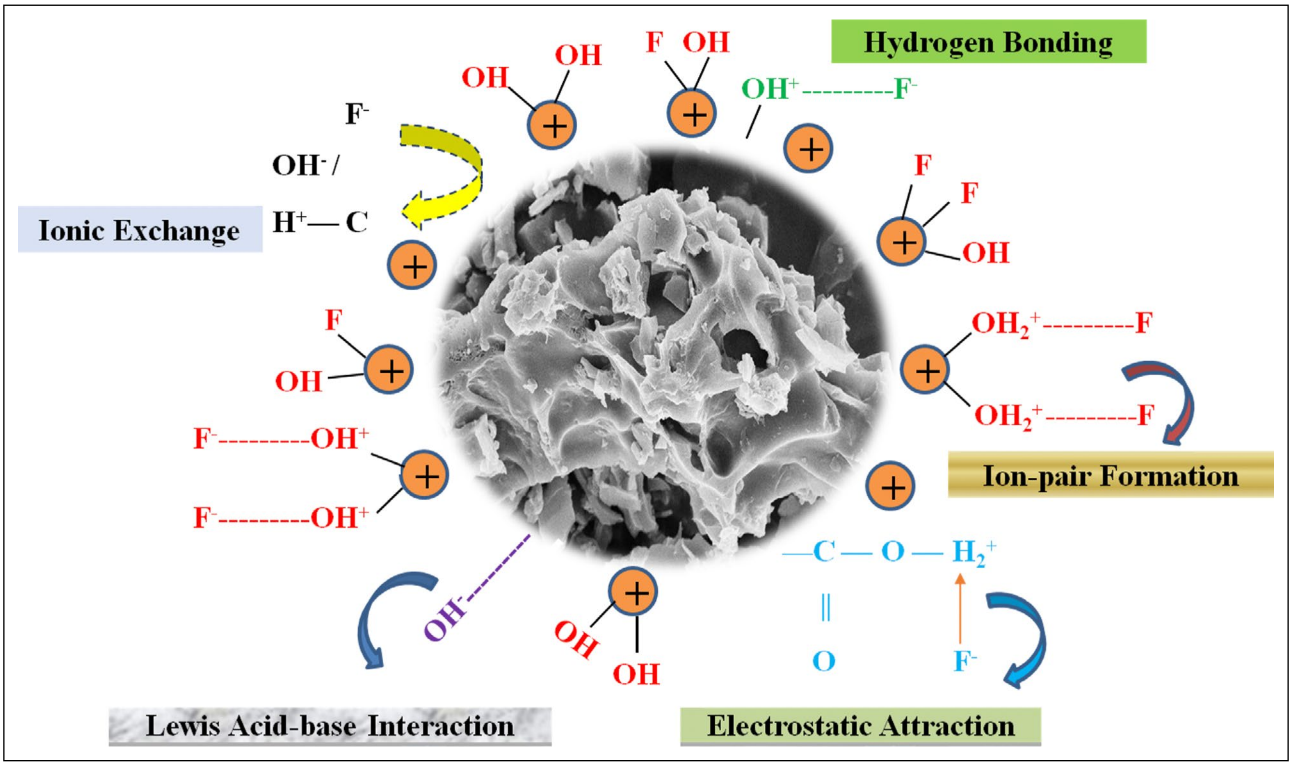

Figure 15. Mechanism of fluoride adsorption onto CSAC800.

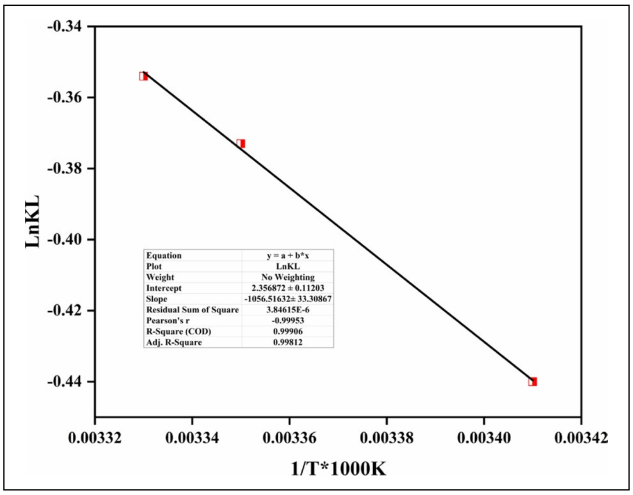

Figure 16. Plot showing the activation energy for the adsorption of F- ions.

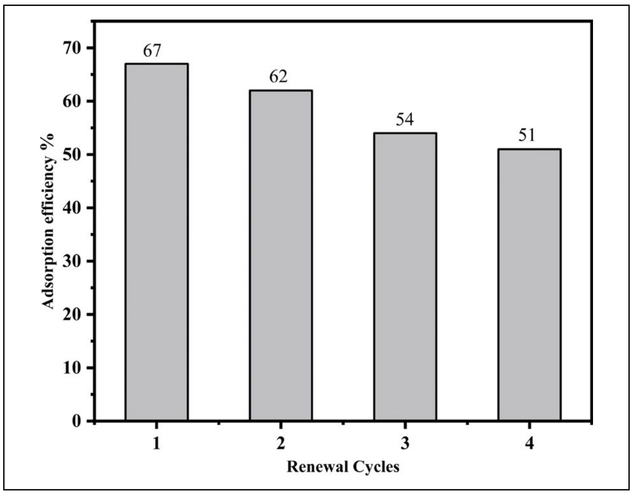

Figure 17. Fluoride adsorption on CSAC800 was investigated over four cycles after regeneration. Initial [F-] was 10 mg/L, with pH 6.0±0.1, 0.5 g/L dose, 25±1°C temperature, and 5-hour contact time.

mented sequentially to eliminate any surplus base quantity. Appropriate repetition interval was chosen for each cycle. As depicted in Figure 17, the adsorbent, following desorption, was subjected to testing for four consecutive cycles for F^- removal. During the initial 1st cycle, the F^- removal percentage stood at approximately 68%, and by the conclusion of the 4th cycle, it had reduced to around 51%. Consequently, this study provided evidence of the CSAC800 adsorbent's ability to be employed for F^- removal across four repeated cycles, after being effectively restored with NaOH processing. Upon 4 renewal stages, the F^- elimination capability has solely dropped by 10%.

CONCLUSION

Chestnut shell-derived activated carbon was employed for the elimination of fluoride ions from water-based solutions. The efficacy of different composite materials (CSC800, CSCAC600, CSAC700 and CSAC800) was evaluated under different conditions, and the resulting order of effectiveness was as follows: CSAC800> SCAC700> SCAC600> CSC800. The prepared materials underwent characterization through the utilization of scanning electron microscopy (SEM), Fourier-transform infrared spectroscopy (FTIR), and Brunauer-Emmett-Teller (BET) techniques. CSAC800 exhibited a measured BET surface area of 912.38 m^2/g and a pore volume of 0.188 cm^3/g. SEM analysis indicated that the material possessed a porous and uniform structure, with the CSAC800 sample exhibiting a higher number of cavities. Among the carbon samples CSAC800, displayed the fewest cavities, but it had a larger pore size. Furthermore, FTIR analysis corroborated the presence of multiple bonds, among other chemical bonds. The performance evaluation of the CSAC800 material revealed that a dosage of 0.5 g/L was sufficient to reduce the fluoride concentration to less than 2.5 mg/L. The maximal adsorption capability for CSAC800 was determined to be 78.69 mg/g, while for CSAC700, it was found to be 26 mg/g. In batch experiments, a contact time of 5 hours (300 minutes) was identified as the optimal duration. Additionally, the pseudo second order model provided a better fit for CSAC800 materials in describing the adsorption kinetics. The adsorbent's reusability was evaluated through consecutive adsorption and regeneration studies, employing 0.01 M NaOH as the eluent. The findings indicated that even after four (4) regeneration cycles, the adsorption capacity only experienced a marginal decline of 10%, demonstrating the adsorbent's favorable potential for multiple uses. The elimination of fluoride through adsorption is an intricate procedure, entailing numerous physical and chemical interactions between the fluoride ions and the adsorbent material.

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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.

USE OF AI FOR WRITING ASSISTANCE

Not declared.

ETHICS

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

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Research Article

Evaluation of metal contamination and ecological risk in surface sediments of an industrialized catchment: A case study of the Saz-Çayırova catchment, Northwestern Türkiye

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ABSTRACT

Investigating the spatio-temporal variations of metal pollution in the sediment of an industrialized watershed, this study aims to identify ecological risks. Utilizing six risk assessment indices—enrichment factor (EF), geo-accumulation index (I-geo), potential ecological risk (RI), contamination factor (CF), ecological risk assessment (ER), and Pollution Load Index (PLI)—the research distinguishes between anthropogenic and geogenic sources. Surface sediment samples are collected from nine locations (comprising seven monitoring sites and two reference sites) across the watershed during both dry and wet seasons. Reference concentrations, tailored to accurately reflect local characteristics, are employed to compute the indices. Results indicate significantly elevated concentrations of Zn, Pb, Cr, Cd, and Ni throughout the basin, exceeding reference values by factors of 15, 20, 5, 10, and 5, respectively. Wet and dry season assessments reveal varying I-geo and EF values across monitoring stations. Cd emerges as the primary ecological risk, predominantly attributed to industrial discharges. Moreover, dry season contamination surpasses that of the wet season. Comparative analysis of the indices reveals PLI's efficacy for spatial assessments, while RI analysis better elucidates temporal variations. In conclusion, this study provides valuable insights for devising strategies to mitigate sediment contamination in industrial watersheds.

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INTRODUCTION

Heavy metals are regarded essential pollutants for aquatic ecosystems due to their high toxicity, persistence, and biogeochemical accumulation potential [1]. In the last decade, heavy metal pollution has posed a serious environmental threat, particularly with the substantial increase in population and intensive industrialization [2]. Heavy metals reach the aquatic environment through both geogenic and anthropogenic channels, such as geological weathering, soil erosion, intensive transportation, mining, agriculture, and industrial operations that involve hydrolysis and oxidation mechanisms [3, 4]. One of the most important ecological risk of heavy metals is accumulation potential in sediments. The sediments directly affect the quality of water column by decomposing organic matter, leading to the release of macro elements (N, P etc.) and toxic heavy metals, and decreasing the oxygen level of the aquatic system [5]. In this case, the flora and fauna (benthic organisms, carinate, fish, and aquatic plants etc.) are deteriorated irreversibly. Hence, assessment of heavy metal contamination in sediments is critical to determine the pollution level and ecological risks of streams.

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Sediments have frequently been defined as reservoir for a wide variety of pollutants, particularly for heavy metals [6, 7]. In recent studies on sediment quality assessment, the negative impacts of heavy metals on ecology have been evaluated by means of the defined pollution indices [8–10]. In this context, various quality indices including contamination factor (CF), enrichment factor (EF), geo-accumulation index (I-geo) and ecological risk assessment (ER) have been implemented for the assessment. These indices provide advantages such as being simple to use and allowing comparisons across stations with different geographical characteristics, since their background equations are based on normalization. In addition to these advantages, they have disadvantages such as neglecting the reactive properties of heavy metals, not taking into account the changes in heavy metal/reference element ratios due to natural processes, and not being able to determine the weight factor for each heavy metal. Several studies conducted in complex industrialized basins have reported that EF, CF, I-geo indices can give inconsistent results in terms of estimating metal pollution [11–13]. This inconsistency leads to significant uncertainties in the assessment of ecological risk regarding to sediment contamination. Yu et al. [13] have reported that the inconsistency obtained from these indices may be related to the background values and further studies on sediment quality will be needed. Therefore, it is critical to determine the site-specific background values in order to maintain the consistency of the results. Furthermore, in these research, it was suggested to interpret many indices by applying them together rather than relying on a single index.

Several research have utilized recognized global average concentrations, sediment quality criteria, or prior studies performed in or near the examined watershed as reference values [13–15]. Accepting a global reference value on a watershed basis, on the other hand, can lead to high uncertainty due to geogenic, physical, and chemical processes that reflect the local characteristics of the studied watershed [16]. The reference values in sediment quality guidelines, which are based on developed countries, may result in the identification of previously unmonitored industrialized watersheds, as highly dangerous. In such watersheds, the measured values at reference stations, determined through field campaigns based on different soil types and land uses, are essential for assessing the local ecological status of the watershed [8–10].

In Türkiye, various studies have been conducted to determine sediment quality in watershed scale [7, 16–18]. In these studies, the lakes and rivers negatively affected by anthropogenic activities including continuous discharge of artificial pollutants (organic matter and heavy metals) induced by mining, energy generating and complex industrial activities have been reported. These studies focused on a specific pollutant by choosing basins with relatively similar land use and a single branch of industry. In contrast, the watershed area of Saz-Çayırova Stream is a unique aquatic ecosystem in which hydromorphological degradation, complex industrialization, agricultural activities, residential areas, transportation, and abandoned mining activities experienced. This area is ecologically important due to its location within the Türkiye's most important industrial cities of Istanbul and Kocaeli, and the Saz-Çayırova Stream flowing into Sea of Marmara, an inland sea of Türkiye. Any comprehensive sediment metal contamination and ecological risk assessment has not been implemented for the watershed. In the studies conducted on the site, superficial examinations on water quality and land cover changes have only been reported [19–22].

In the light of abovementioned information, this study aims to reveal the temporal (wet and dry periods) and spatial distributions of metal pollution in the sediment of Saz-Çayırova Stream. In this context, ecological risk assessment techniques were used to identify natural and anthropogenic sources of sediment pollution in the watershed. Furthermore, reference values specific to the watershed were calculated based on land use and soil types and compared to other reference values. The outputs of this research are thought to serve decision-makers conduct remediation projects along the stream by identifying metal pollution accumulation regions in the Saz-Çayırova.

MATERIAL AND METHODS

Site Description

The catchment of Saz-Çayırova (40° 45'–40° 52' N, 25° 21'–25° 27' E) is located between the borders of Istanbul and Kocaeli Provinces. The watershed area and average elevation of this catchment are approximately 50 km^2 and 100 m, respectively (Fig. 1). The drainage area and length of the stream, classified as a small-scale basin, is approximately 20 km^2 and 10 km, orderly [19]. Residential and industrial areas constitute 73% of the watershed, with individual agricultural lands accounting for 21% and forests accounting for 6% [23]. Furthermore, Saz stream tributaries serve as a receiving environment for the treated wastewater of two Organized Industrial Zones (OIZ-1 and OIZ-2) in the basin's northern region. These regions are composed of approximately 39.7% automotive sub-industry, 20.48% metal industry, 11.7% chemical industry, and 10.4% other manufacturing industries (Fig 1c). The effluents from these industries are rich in heavy metal and nutrient concentrations due to production processes such as dyeing, washing, and phosphating. Other hand, considering that there are 20,000 and 24,000 personnel in OIZ-1 and OIZ-2, respectively, domestic wastewater discharges are also a concern [24].

The elevation in the watershed area varies between sea level and 313 meters. Due to the relatively high elevation difference in the basin, stream energy increases in the downstream parts. In addition, digitized soil maps containing the slope groups and main soil groups are illustrated in Fig 1b and Fig 1d. The watershed is located in the transition zone between the Mediterranean and the Black Sea climate characterized by cold rainy winters, and hot humid summers. The annual average precipitation and temperature are 720 mm, and 15 °C, respectively. The catchment is under prevailing wind direction of NE (70%) [22].

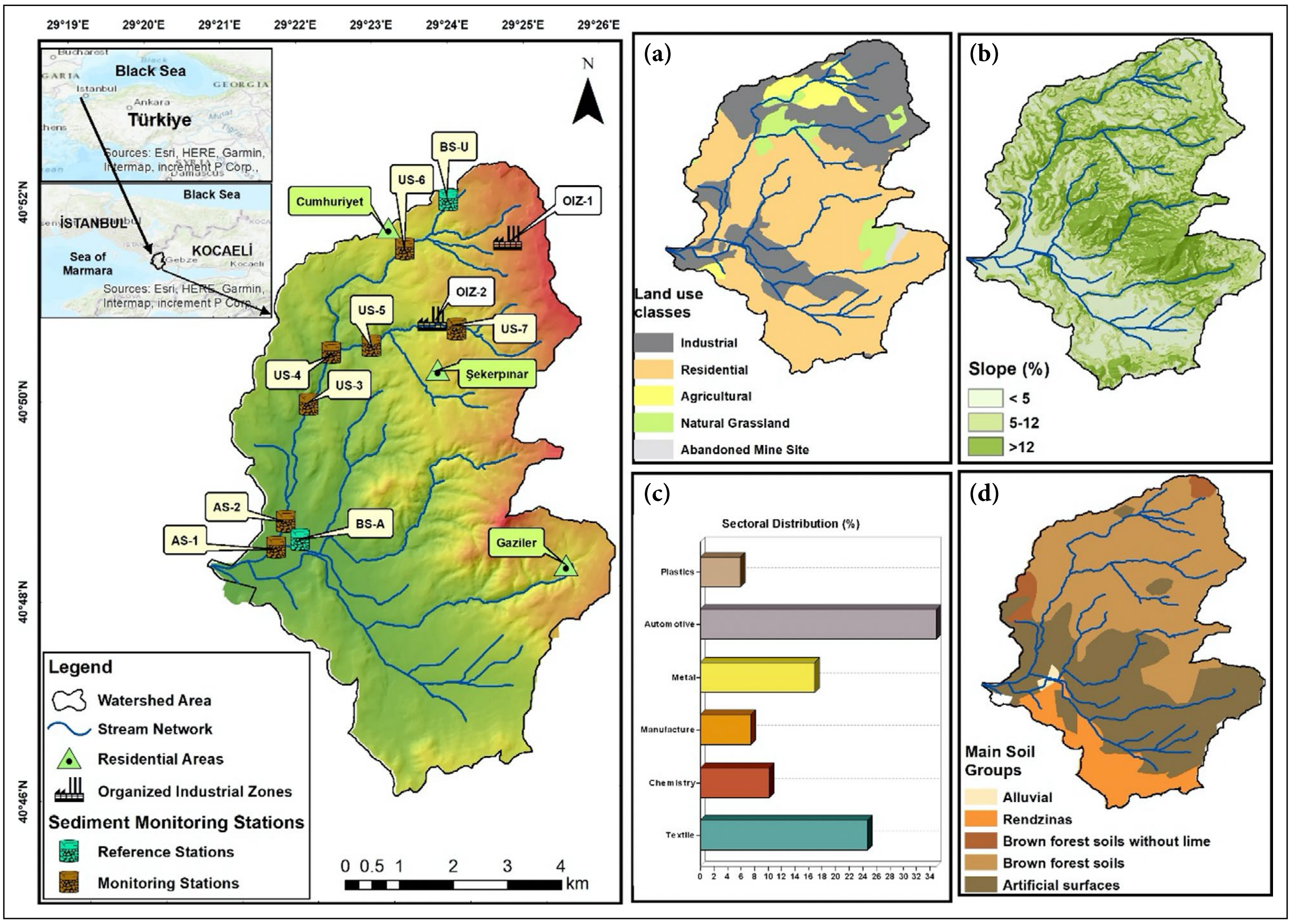

Figure 1. Location map of Saz-Çayırova watershed, **(a)** land use map, **(b)** slope classes, **(c)** sectoral distribution (%) of industries in OIZs, **(d)** main soil groups.

Field Campaigns and Sampling Strategy

The Çayırova stream was rehabilitated by being channelized into concrete after the flood in 2010. Therefore, sediment does not adhere to or accumulate on the concrete floor, especially in the lower part of the Çayırova stream. In this context, sediment quality and potential ecological risk analyzes were carried out only on Saz Stream tributaries. The selection of the sediment sampling stations took into consideration the residential and industrial zones, the stream morphology, and highways. Field campaigns were organized in August and December 2020 to represent dry and wet periods. Surface sediment (0–15 cm) samples were collected at 7 different stations in both periods. Approximately five kilograms of samples were collected with a steel trowel at each sampling station and stored in ten-liter glass jars. Samples were transported to the laboratory in a cooler and then stored in a refrigerator set at 4.0 °C.

The locations of reference stations have been determined by the Instute of Mineral Research and Exploration (MTA) based on digitized geological maps and land use/land cover distribution. Additionally, the number of reference stations has been determined in accordance with the distribution of main soil groups found in the Türkiye National Soil Database (TNSD). The main soil groups of the watershed are distributed as follows (Fig. 1d): Artificial surfaces (35%), brown soils without lime (37.5%), brown forest soils (11%) and rendzinas (16.5%). The selected monitoring stations along the Saz Stream are situated within regions characterized by brown soils without lime and artificial surfaces. In this regard, two reference stations were selected: BS-U, representing background station for brown forest soils without lime, and BS-A, representing background station for artificial areas. These stations were selected from locations with minimal anthropogenic influence and represent different main soil groups. While the BS-U serves as the reference values for stations between US-3 and US-7, the BS-A was defined as the reference for AS-1 and AS-2 stations. The reference concentrations determined within the scope of this study were compared, with values used at national and international scales.

Laboratory Analysis

The surface sediments collected were first dried in an oven at 105 °C for four hours. After each sample was sieved with a 63 μm diameter sieve, 0.25 grams of sediment sample was burned in a microwave oven (Milestone Ethos 1600) with an acid mixture (HNO_3 – 4 ml, HF-2 ml, $HClO_4$ -1 ml, H_2O_2–1 ml) in a total volume of 8 ml [25–29]. Afterwards, the samples were diluted to 25 ml with ultrapure water and filtered. All metal analyzes were determined by Inductively Coupled Plasma-Optical Emission Spectrophotometry (ICP-OES, Optima 7000 DV, Perkin Elmer). Preservation,

Table 1. Classification of enrichment factor (EF), geo-accumulation index (I-geo), potential ecological risk (RI), contamination factor (CF), ecological risk assessment (ER) and Pollution Load Index (PLI)

EF scale	Enrichment Level [32]	I-geo classes	Pollution Level [35]
EF<1	No enrichment	I-geo<=0	Unpolluted
EF=1–3	Minimal enrichment	I-geo=0–1	Unpolluted to moderately polluted
EF=3–5	Moderate enrichment	I-geo=1–2	Moderately polluted
EF=5–10	Moderately severe enrichment	I-geo=2–3	Moderately to strongly polluted
EF=25–50	Very severe enrichment	I-geo=3–4	Strongly polluted
EF>50	Extremely severe enrichment	I-geo=4–5	Strongly to very strongly polluted
ER classes	ER Level [38]	CF classes	Contamination Level [37]
ER<40	Low potential ecological risk	CF<1	Low contamination
ER=40–80	Moderate potential ecological risk	CF=1–3	Moderately contaminated
ER=80–160	Significant potential ecological risk	CF=3–6	Considerably contaminated
ER=160–320 & >320	High & Very high potential ecological risk	CF>6	Very high contamination
RI classes	Risk Level [37]	PLI	PLI İndexes [36]
RI<150	Low Ecological risk	PLI<0	Unpolluted soils or sediments
RI=150–300	Moderate ecological risk	PLI=0	Perfection
RI=300–600	Significant ecological risk	PLI=1	Baseline levels of pollutants
RI >600	High ecological risk	PLI>1	Progressive deterioration of the site quality

EF: Enrichment factor; (I-geo): Geo-accumulation index; RI: Potential ecological risk; CF: Contamination factor; ER: Ecological risk assessment; PLI: Pollution load index.

transportation and analysis of sediment samples were carried out according to standard methods [30]. Analytical data quality was ensured by careful standardization, procedural blank samples, and duplicate measurements [31].

Heavy Metal Pollution Indices

In this study, total concentration-based enrichment factor (EF), geo-accumulation index (I-geo), potential ecological risk index (RI), pollution load index (PLI) and ecological risk assessment (ER) indices were used to assess the potential ecological risks of metals in surface sediments. Output of these indices were interpreted according to the following scales (Table 1).

The enrichment factor (EF) is generally used a convenient method to distinguish between geogenic and anthropogenic sources by normalizing chemical components according to their reference values. In many studies, Fe, Al and Ti were recommended as a reference element in EF calculation [32, 33]. The single element normalization approach may cause uncertainty due to the effect of sediment texture changes on the metal concentrations [13, 34]. Furthermore, empirical cumulative density plot and Shapiro-Wilk normality test (alpha <0.05) were applied whole dataset to see outlier values and data distribution, respectively. In our case, Al and Fe was taken as reference element due to do not reveal outlier values and fitted normally distribution. From another perspective, the proximity of the measured concentrations of Al and Fe elements at monitoring stations to those of reference stations supports the suitability of these elements as reference elements. The EF is expressed mathematically [32];

$$EF = \left[\frac{(C/_{Al})_{sample}}{(C/_{Al})_{reference}} + \frac{(C/_{Fe})_{samples}}{(C/_{Fe})_{reference}}\right]/2 \quad (1)$$

Where C represents the investigated element; Al and Fe are the reference/background elements.

The geo-accumulation Index (I-geo) was proposed by Müller [35] and is widely preferred for evaluating metal/metalloids levels. I-geo was calculated as follows;

$$I_{geo} = \log_2\left(\frac{C_{sample}}{1.5\ x\ B_{sample}}\right) \quad (2)$$

where C_{sample} is the analyzed concentration (mg/kg) of metal/metalloids in the sample sediment, B_{sample} is the geochemical background value (mg/kg) of the element in the background samples and the factor 1.5 is defined to minimize the effects of possible variations in the background values which may be attributed to lithogenic effects [35]. Measurements from the BS-U and BS-A stations were used to determine reference values for the Saz-Çayırova watershed.

The ecological risk assessment of the watershed was evaluated using the ecological risk index (RI) and the Pollution Load Index (PLI). PLI and RI were calculated as a fraction of the contamination factor (CF) that evaluates the contamination level of a single heavy metal. CF is calculated as follows;

$$CF = \frac{C_{sample}}{C_{reference}} \quad (3)$$

where C_{sample} is the concentration of evaluated metal in the sediment sample and $C_{reference}$ is the background concentration of the heavy metal, specified to the watershed. PLI indexates contamination of metals evaluated for a single monitoring site [36]. It is calculated as a fraction of the CF values;

Table 2. Comparison of reference concentrations (mg/kg) of metals measured with previous studies

Examined elements (mg/kg)	Other studies					This study	
	Coşkun et al. [41]	Yılmaz et al. [42]	Mason [43]	Taylor et al. [46]	Turekian [47]	BS-U	BS-A
Al	–	–	81.300	–	25.000	246.273	88.622
Ti	5.000	–	–	–	1.500	1.512	8.672
Fe	40.000	38.000	50.000	35.000	9.800	68.303	91.134
Ni	50	37	75	75	50	37	100
Cu	30	33	55	55	45	260	327
Zn	90	72	–	–	16	180	729
Cd	BDL	BDL	–	0.2	BDL	BDL	1
Pb	12	37	–	20	20	10	87
Cr	70	61	–	100	90	156	199

*: BDL refers to concentrations below the detection limit.

$$PLI = \sqrt[n]{CF1 \times CF2 \times CF3 \times \ldots . \times CF_n} \quad (4)$$

where, n is the number of metals and CF is the contamination factor.

RI is widely used for ecological risk assessment in soil and sediments [37]. The index has been developed for six toxic metals using the following equations [38].

$$RI = \sum_1^n ER \; ; ER = Tr \times CF \quad (5)$$

where ER is the single index of ecological risk factor, and n is the amount of the heavy metal class, Tr toxic response factor suggested by Hakanson [38] for six metals Ni (5), Cu (5), Zn (1), Cd (10), Pb (5) and Cr (2). ER and RI express the potential ecological risk factor of individual and multiple metals respectively. The expressions and values used for the interpretation of the potential ecological risk factor were reported in Table 1.

RESULTS AND DISCUSSIONS

Assessments of Background Metal Concentrations (mg/kg) in Surface Sediments

Reference concentrations that accurately reflect the local characteristics of a watershed are substantial for the scientific computation of the ecological risk status of that watershed [39, 40]. Because of this, before discussing the results, similarities and differences between the reference values determined within the scope of this research and the reference values commonly used in national and international studies have been discussed (Table 2). While international studies were selected to encompass research on the elements examined in our study, national studies were attempted to be identified among research conducted in regions as close as possible to the Saz-Çayırova.

If we briefly summarize the studies comparing reference values, Coşkun et al. [41] examined the chemical composition of 73 surface soil samples across the Thrace Basin, covering an area of 24,000 km². Additionally, Yılmaz et al. [42] evaluated the chemical composition of 14, 6, and 10 surface soils based on three different land-use classes, namely industrial, urban, and rural areas, in the Izmit Gulf. To compare with the reference values in our study, the average of 30 stations from Yılmaz et al. [42] was calculated and a comparison was made. Mason's [43] study determined the background levels of 23 elements as a consequence of topsoil structure analyses, and these values were used as reference values in numerous subsequent studies on the issue [44, 45]. Taylor et al. [46] also investigated surface soils and contributed to the literature by reporting background concentrations of 22 elements. Turekian [47] analyzed soil samples from 17 distinct locations in the Chattanogour Plateau River Basin, which has a tropical environment, both post- and pre-monsoon. Because of the low anthropogenic influence in the stated area, this study was also used as a reference value in several ecological risk assessments [48, 49].

The Al concentrations observed at BS-A were consistent with Mason's [43] reference values (Table 1). In general, Fe, Ni, Cu, Zn, Cd, Pb, and Cr concentrations measured at the BS-A were found to be higher than in other studies. In particular, Zn, Cu, and Pb appear to be approximately ten times higher than those of the other studies. These high concentrations can be associated with an abandoned metallic sulfide mining site located in the northwest and southeast sectors of the Saz-Çayırova, which has an approximate reserve of 110,000 tons of Pb, Zn, and Cu. In the examined studies, only Taylor et al. [46] measured Cd over the detection limits (0.2 mg/kg), and this amount is around one-fifth of the Cd concentration in our analysis.

Al and Fe levels at the BS-U reference site, which represents brown forest soils without lime, were found to be high relative to other studies. Iron and aluminum oxides tend to accumulate in this type of soil, especially due to humid and hot climatic conditions [50]. In this status, comparatively high reference values for Al and Fe might be considered an expected condition. This study noticed that the Cd concentration was lower than reported in other studies and similar to the value detected by Yılmaz et al. [42]. Yılmaz et al. [42]'s

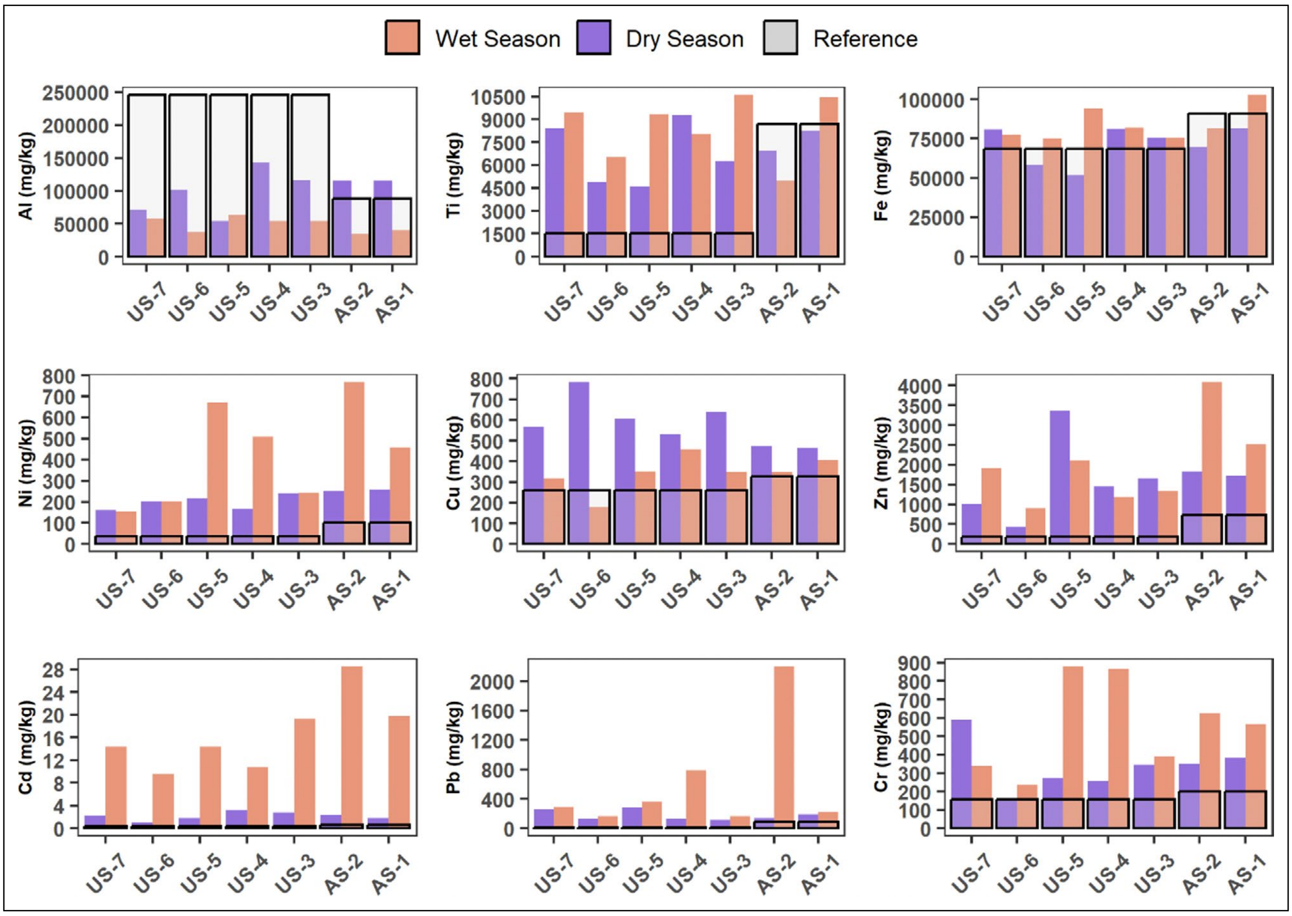

Figure 2. Spatio-temporal variation of metal concentrations throughout the Saz-Çayırova and their comparison with reference concentrations.

research region is close to the Saz-Çayırova basin, which can explain the similarities. The observed Pb was similar to that found by Coşkun et al. [41] and lower than in other studies. Cu, Zn, and Cr concentrations were significantly high relative to the studies compared.

The metal concentrations measured in BS-A and BS-U exhibit both similarities and differences compared to other studies. For instance, despite the proximity of the watershed examined by Yılmaz et al. [42] to Saz-Çayırova, differences were observed in Fe, Al, Cu, and Zn concentrations. This example demonstrates the importance of identifying the local ecological risk dimension of a watershed based on the relatively clean stream network within the studied watershed.

Seasonal and Spatial Variation of Examined Metals

As a preliminary assessment of ecological risk analysis methods, Figure 2 illustrates the seasonal and spatial variations of the examined elements in the watershed, supported by concentrations obtained at reference sites. The concentrations of Al, Ti, and Fe did not differ significantly between the dry and wet seasons, except for some sites. Al concentrations in AS-1 and AS-2, which represent the downstream parts of the watershed, were measured to be high in the wet season. Ti concentrations at US-6 and US-5 were around 1.5 times higher during the dry season than during the wet season.

Ni and Cr were measured to be three times higher in the dry season than in the wet season in the US-4 and US-5. The two stations mentioned represent the outlets of the different stream tributaries (Fig. 1). That's why, there might have been a tendency for the accumulation of nickel and chromium in the surface sediments of the tributary outlets, accompanied by a decrease in the river's energy due to relatively low flow conditions (Fig. 2). Cd and Pb concentrations were significantly higher during the dry season. Pb and Zn levels are roughly 20 and 4 times measured in the dry season relative to wet season, particularly at AS-2 site. There is heavy vehicle and truck traffic approximately 100 meters north of AS-2. It is noted that the main pollutants released into the atmosphere from exhaust emissions are Pb and Zn, and they tend to fall on the earth through atmospheric inversion [51]. In this context, this high difference between the dry and wet season can be associated with vehicle and truck emissions. From another perspective, this can be linked to the transport of metals by surface water, as relatively high flow conditions during the wet season minimize metal accumulation in sediment.

Spatially, except for Zn, the elements investigated for the wet season did not show a high variation from the upstream to the downstream of the watershed. In the dry season, all metals except Al, Ti, Fe and Cu have high variation. It can be said that discharges from individual

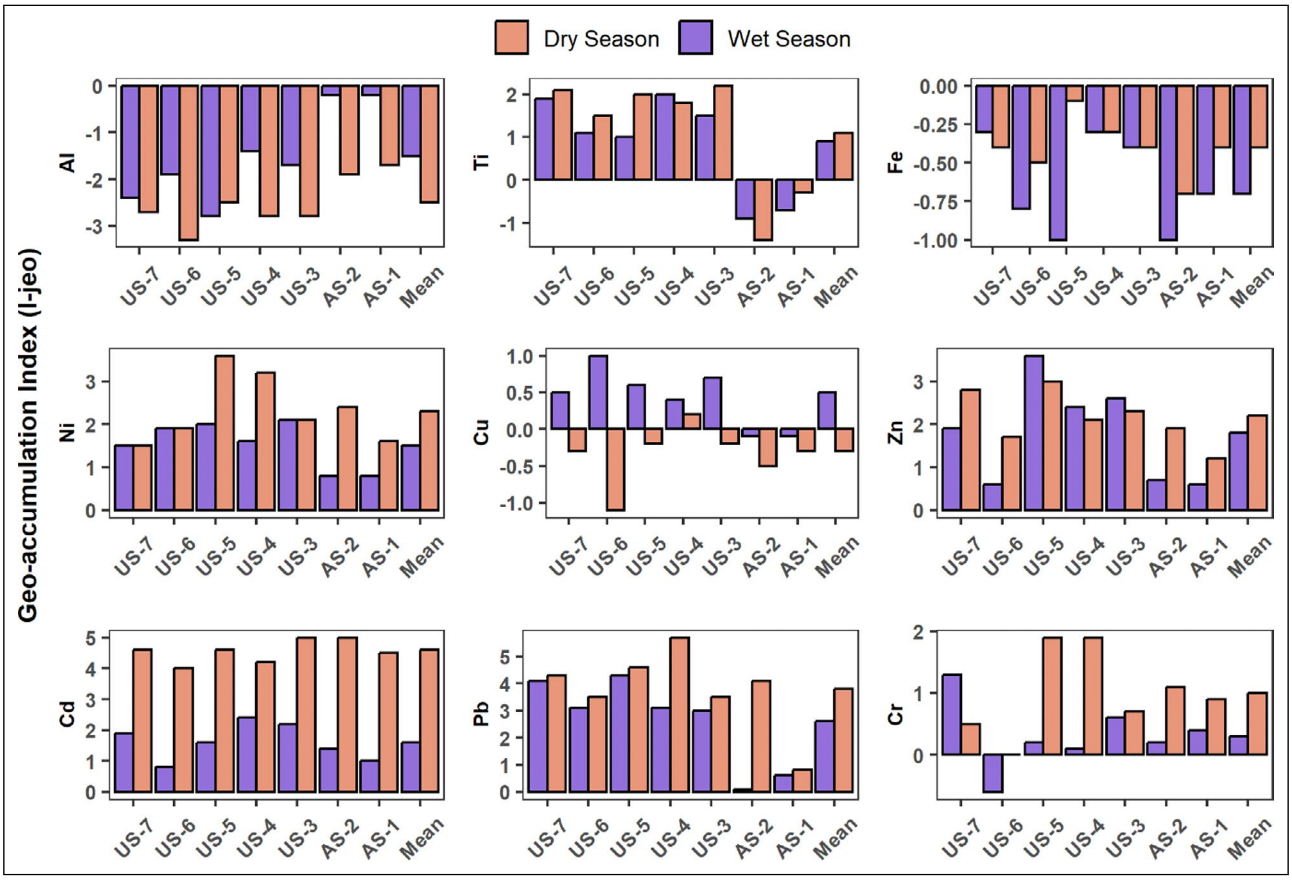

Figure 3. Geo-accumulation (I-geo) values of the metals analyzed in surface sediments.

industries detected by field observations are important factors that trigger the high variation in the dry season. Throughout the watershed, all metals (except Al and Fe) were measured significantly higher than the reference values. Specifically, it was seen that the Zn, Pb, Cr, Cd, and Ni were about 15, 20, 5, 10, and 6 times greater than the reference values, respectively. This clearly illustrate the impact of local activities on surface sediments, especially during the dry season.

Metal Pollution Indices

Enrichment Factor (EF)

EF values were calculated for the wet and dry seasons to identify natural and anthropogenic sources of metal concentrations (Table 3). Al and Fe were excluded from the analysis as they served as reference elements.

During the dry season, all stations showed the extremely severe enrichment Cd enrichment, indicating that this element was the principal contaminant compromising sediment quality. Pb concentrations showed very severe enrichment (US-3) and extremely severe enrichment (US-7, US-6, US-5, US-4, and AS-2). Cr and Ni elements have moderate enrichment in all stations except US-5, US-4 and US-3. That is, very severe enrichments of Pb, Ti, Ni, and Cr were recorded in the two tributaries under industrial pressure (US-4 and US-5), as well as at combination of two tributaries (US-3). US-4, the receiving environment of OIZ-1, demonstrated the highest Pb and Ni enrichment, implying these tributaries act as metal reservoirs. This localized accumulation necessitates further study of potential impacts and solutions. The Cu was minimal to moderately enriched across the entire watershed while the Zn exhibited very severe enrichment all of sites, except AS-1.

During the wet season, the strongest enrichment was observed in Pb values, and all stations except AS-2 and AS-1 showed very severe enrichment (US-6, US-4, US-3) and extremely severe enrichment (US-7, US-5). The minimal enrichment recognized at the AS-2 and AS-1 sites is directly related to the high Pb concentration (87 mg/kg) reported at the BS-A which represents the reference value for artificial surface. The highest enrichments of Zn were calculated at US-5 (EF = 45.4) and US-7 (EF = 11.8). Given that these sites are situated along the tributaries under the influence of OIZ-2 discharges, it is reasonable to attribute the primary source of zinc in this tributary to OIZ-2 discharges. At the US-5, EF values of the Ti, Ni, and Cd were categorized as extremely severe enrichment. Analyses strongly support that Zn, Ni, Ti, and Cd enrichments originate from OIZ-2 discharges. Because the OIZ-2 includes numerous sectors, such as metal, plastic, textile, and chemical product manufacturing, the wastewater produced by these sectors contains elements such as Zn, Ni, Cd, Ti, As, and Cu [22]. In addition, Cr concentrations had lower EF values than other elements.

Table 3. Enrichment factors (EF) determined in surface sediments throughout the Saz-Çayırova

Sites	Seasons	Ti	Ni	Cu	Zn	Cd	Pb	Cr
US-7	Wet	11.9*	7.8	3.9	11.8*	10.2	65.4**	4.8
	Dry	16.1*	9.2	2.4	23.3*	80.6**	51.4**	6.9
US-6	Wet	5.9	18.8*	4.2	3.2	3.5	17.7*	1.4
	Dry	16.5*	7.5	2.4	17.3*	84.3**	57.3**	5.3
US-5	Wet	10.9*	14.2*	5.6	45.4*	11.1*	69.8**	4.3
	Dry	14.3*	32.8*	2.7	23.6*	74.3 **	74**	11.4*
US-4	Wet	7.9	4.2	1.9	7.6	7.7	12.3*	1.6
	Dry	14.4*	36.7*	4.2	15.6*	65.7**	191.5**	13.3*
US-3	Wet	6.2	7.6	2.9	10.8*	8.4	14.0*	2.6
	Dry	19.3*	15.4*	3.1	17.6*	116.0**	38.8*	15.9*
AS-2	Wet	0.8	2.5	1.5	2.5	4.0	1.6	1.8
	Dry	1.1	16.5*	2.3	12.0*	102.2**	54.1**	6.7
AS-1	Wet	0.9	2.3	1.3	2.1	2.7	2.0	1.7
	Dry	1.9	7.0	1.9	5.2	50.1**	3.8	4.3
Average	Wet	7.1	8.2	3.0	11.9*	6.8	26.1*	2.6
	Dry	11.9*	17.9*	2.7	16.4*	81.9**	66.7**	7.7

*: Represents elements included in the very severe enrichment. **: Represents elements included in the extremely severe enrichment.

In the wet season, average EF values across measurement sites follow the descending order: Pb > Zn > Ni > Cd > Ti > Cu > Cr. In the dry season exhibits a distinct pattern with Cd > Pb > Ni > Zn > Ti > Cr > Cu. Different enriched elements suggest that surface sediment chemistry in the Saz-Çayırova basin is dynamically influenced by seasonal variations. The observed seasonal variations in dominant enriched elements can be attributed to two key factors: (i) increased accumulation of industrial pollutant loads within sediments during low-flow conditions, favoring their retention, and (ii) individual agricultural activities carried out in the US-6 region during the dry season (Fig. 1a).

Geo-Accumulation Index (I-geo)

Geo-accumulation values (I-geo) of the elements examined within the scope of the study were visualized in Figure 3. As expected, Al and Fe exhibited consistently unpolluted levels (I-geo ≤0) throughout the watershed. Other elements demonstrate various pollution level, ranging from Unpolluted to moderately polluted (I-geo=0-1), moderately polluted (I-geo=1-2), moderately to strongly polluted (I-geo=2-3), strongly polluted (I-geo=3-4), and strongly to very strongly polluted (I-geo=4-5). These variations were linked to the combined influence of localized activities within the watershed and natural geochemical processes.

In the dry season, Cd and Pb indicated the highest I-geo values. Cd levels were consistently classified as strongly to very strongly polluted across all sites, with relatively low spatial variation. Pb values represented strongly polluted at all stations except AS-1 (Unpolluted to moderately polluted) and US-3 (strongly polluted). Zn and Ni displayed the highest I-geo value at the US-5 and the lowest value at the AS-1. Ti indicated moderately to strongly polluted level in the Saz tributaries. However, with the addition of the Çayırova tributaries, Ti clustered to the unpolluted class. This observation is directly related to the relatively high Ti concentration measured in BS-A. The Cr caused moderately polluted at the US-4 and US-5, while clustering unpolluted levels at other stations. The negative I-geo values observed for the Cu element throughout the watershed (except US-4) point out the absence of sediment contamination and suggest that the Cu found in the sediment originates primarily from natural processes such as soil or rock weathering.

During the wet season, Pb and Zn demonstrated the highest I-geo values, followed by Cd and Ni. The high contamination originating from these elements was calculated in the US-5 and US-7. Considering that these tributaries were influenced by OIZ-2 discharges. Hence, the primary source of Pb, Zn, Cd, and Ni contamination in surface sediments can be attributed to OIZ-2 discharges. The highest and lowest I-geo values for Ti were recorded at US-4 and AS-2, respectively. This illustrates that Ti-rich surface sediments originate from the northern stream tributary. The I-geo values of Cu and Cr indicate unpolluted to moderately polluted throughout the basin, reaching their maximum at the US-7 station. The US-7 station represents the region before the OIZ-2 discharges (Fig. 1). The relatively high I-geo values observed during the wet season can be attributed to erosion.

The average I-geo values of the monitoring stations in wet and dry seasons ranked in descending order are; Pb > Zn > Ni > Cd > Ti > Cu > Cr > Fe > Al in the wet season and Cd

Table 4. Contamination factor (CF) and Pollution Load Index (PLI) values of the Saz-Çayırova

Stations	Seasons	Contamination factor (CF)									PLI
		Al	Ti	Fe	Ni	Cu	Zn	Cd	Pb	Cr	
US-7	Wet	0.3	5.6*	1.2	4.3*	2.2	5.6*	5.6*	26**	3.8*	3.4
	Dry	0.2	6.3**	1.1	4.2*	1.2	11**	37**	29**	2.2	3.9
US-6	Wet	0.4	3.3*	0.8	5.5*	3.0	2.4	2.5	13**	1.0	2.2
	Dry	0.1	4.3*	1.1	5.4*	0.7	5.0*	24**	17**	1.5	2.7
US-5	Wet	0.2	3.0	0.8	5.8*	2.3	19**	4.6*	29**	1.8	3.1
	Dry	0.3	6.2**	1.4	18**	1.3	12**	37**	37**	5.6*	5.5
US-4	Wet	0.6	6.1**	1.2	4.5	2.0	8**	8.1**	13**	1.7	3.4
	Dry	0.2	5.3*	1.2	14**	1.8	6.5**	28**	80**	5.6*	5.2
US-3	Wet	0.5	4.1*	1.1	6.5**	2.5	9.1**	7.1**	12**	2.2	3.4
	Dry	0.2	7.0**	1.1	6.5**	1.3	7.5**	49**	17**	2.5	3.9
AS-2	Wet	1.3	0.8	0.8	2.5	1.4	2.5	4.0*	1.7	1.8	1.6
	Dry	0.4	0.6	0.9	7.7**	1.1	5.6	48**	25**	3.1*	3.2
AS-1	Wet	1.3	1.0	0.9	2.6	1.4	2.3	2.9	2.2	1.9	1.7
	Dry	0.5	1.2	1.1	4.6*	1.2	3.5	33**	2.5	2.8	2.4
Average	Wet	0.7	3.4*	1.0	4.5*	2.1	7.0**	5.0*	14**	2.0	2.7
	Dry	0.3	4.4*	1.1	8.6**	1.2	7.2**	36**	30**	3.3*	3.8

*: Represents elements included in the considerably contaminated class (CF=3–6). **: Represents elements included in the very high contamination class (CF>6).

> Pb > Ni > Zn > Ti > Cr > Cu > Fe > Al in the dry season. The highest I-geo values in both seasons can be explained by the reasons mentioned in the EF analysis. Furthermore, a high consistency is observed between I-geo and the EF analysis results. This strong consistency indicates that metal pollution indices serve as a significant reference for evaluating ecological risk assessment.

Ecological Risk Assessment Indices

Contamination Factor (CF) and Ecological Risk Assessment (ER)

Contamination factor (CF) values were found to be similar to those of EF and I-geo analyses (Table 4). This can be attributed to the fact that all three analyses rely on similar mathematical equations, despite employing different normalization techniques. The mean Pb and Zn values indicate a very high contamination level in both wet and dry seasons, while Cd and Ni included this group in the dry season. The mean Cr values obtained for the dry season and Ti also emerge as considerable pollutants across the watershed.

Ecological Risk Assessment (ER) results refer to lower potential risk classes (low-medium-significant) against the previous three analyzes (EF, I-geo, CF). For instance, although Pb was the element with the high enrichment and contamination throughout the watershed, it was clustered in the low, moderate, and significant potential ecological risk levels in ER values, except for the US-5 and US-4 (Table 5). A similar situation is valid for Cu, Zn, and Cr elements. In contrast, Cd poses a high and very high potential ecological risk in the dry season for all sites, as calculated in EF, I-geo, and CF techniques. This is related to the toxic response factor (Tr) determined for each heavy metal in the ER calculation. The high Tr value of 10 assigned to Cd, when multiplied by the contamination factor values, reveals Cd as the most critical parameter ecologically for the Saz-Çayırova. The main pollution sources of Cd are metal industries, metal mining, and the refining, production, and application of phosphate fertilizers [52, 53]. Metal industry activities within the watershed seem to affect Cd concentrations more than other heavy metals.

Seasonal and Spatial Variation of PLI and RI Values

The spatial variability of PLI across the Saz stream indicates progressive deterioration of the site quality (PLI>1) during both dry and wet seasons (Fig. 4). In the wet season, PLI peaked at stations US-7, US-4, and US-3, while the lowest values were found in downstream parts of the watershed. During the dry season, the maximum PLI (5.5) was recorded at US-5, while the lowest (2.4) was recorded at AS-1. The average PLI of the wet and dry periods highlights increased pollution in the dry season. Notably, the stations exhibiting maximal Pollution Load Index (PLI) values differ between wet and dry seasons. Besides, all share the key feature of being located on drainage networks impacted by OIZs. This suggests that surface sediments in OIZ-2 influenced stream networks during the dry season and those under OIZ-1 pressure during the wet season pose potential ecological threats.

Table 5. Ecological Risk Assessment (ER) and Potential Ecological Risk Index (RI) values in surface sediments

Stations	Seasons	Ecological risk (ER)					RI
		Cu	Zn	Cd	Pb	Cr	
US-7	Wet	10.9	5.6	167.9*	131.1	7.6	323.0
	Dry	6.1	10.6	1095.5**	148.0	4.3	1264.5
US-6	Wet	15.1	2.4	76.2	64.7	2.0	160.2
	Dry	3.4	5.0	727.4**	82.4	3.1	821.2
US-5	Wet	11.6	18.7	137.2	143.8	3.5	314.9
	Dry	6.7	11.7	1100.9**	182.8*	11.3	1313.4
US-4	Wet	10.2	8.1	244.3*	65.2	3.3	331.1
	Dry	8.8	6.5	825.9**	401.2**	11.1	1253.6
US-3	Wet	12.3	9.1	213.4	59.7	4.5	289.0
	Dry	6.6	7.5	1475.9**	82.3	5.0	1577.2
AS-2	Wet	7.2	2.5	119.8	7.9	3.5	140.9
	Dry	5.3	5.6	1426.6**	126.0	6.3	1569.7
AS-1	Wet	7.1	2.3	88.5	11.0	3.8	112.8
	Dry	6.2	3.5	989.6**	12.6	5.7	1017.5
Average	Wet	10.6	7.0	149.6	69.1	4.0	240.3
	Dry	6.2	7.2	1091.7**	147.9	6.7	1259.6

*: Represents high potential ecological risk level (ER=160–320). **: Represents very the high potential ecological risk level (ER=160–320).

The spatial distribution of Potential Ecological Risk Index (RI) values varies during the wet season (Fig. 4). While AS-1 and AS-2 stations are classified as low ecological risk (RI<150) during the wet season, US-3 and US-6 are classified as moderate ecological risk (RI=150-300). US-7, US-5 and US-4 stand out as significant ecological risk (RI = 300-600). The average RI value for the wet season (RI = 240.3) showed that surface sediments pose a moderate ecological risk. US-5 and US-4 representing outlets of the tributaries before joining the main network, explain their high RI values compared to others. As discussed previously, relatively high background levels at AS-1 and AS-2 contributed to their low RI values.

In the dry season, the distribution of RI values throughout the watershed was similar to PLI values. Across all monitored stations and the average value of RI (1259.6), surface sediments pose a high ecological risk. AS-2 (RI=1569.7) and US-3 (RI=1577.2) carried the distinction of being the highest-risk sites, while US-6 (RI=821.2) was the lowest (Table 4). The Tr values determined for Cd at all stations are the basis for the high RI values. Cd tends to accumulate in surface sediments in the dry season. Many studies have linked the element Cd to colloidal particulates that can be easily transported via surface flow in streams [54, 55]. Essentially, Cd carried by these readily transported colloids, primarily sourced from local industries, generates significantly elevated ecological risk under low-flow conditions.

While PLI and RI values agree in the dry season, a significant difference occurs during the wet season. Both PLI and RI results were impacted by Cd, but RI reveals this influence more distinctly due to fewer included elements. Excluding Cd reclassifies almost all stations (except US-4 in the dry season) as low-risk in RI, highlighting its sensitivity to dominant pollutants. Conversely, eliminating Cd had low effect on PLI's classification of progressive deterioration of the site quality demonstrating its weak ability to identify specific dominant variables. As demonstrated by this example, RI analysis allows for the determination of the dominant pollutant(s) in surface sediments, as well as a more direct effect of the dominant pollutant(s) on the results of this type of analysis. The limitation of RI analysis is that it can only test a total of eight heavy metals, including Cu, Zn, Cd, Pb, and Cr, all of which were investigated in this study.

CONCLUSION

The ever-expanding presence of urbanization and industrialization in watersheds amplifies the current sediment's sensitivity to environmental changes. Frequent activities like recreation, construction, and reclamation directly impact sediment characteristics, posing a risk to the delicate ecological balance. To effectively manage these impacts, high-resolution spatial and temporal monitoring of recipient environment components is crucial. Such data forms the vital foundation for informed pollution prevention strategies. As proven by this research, monitoring and char-

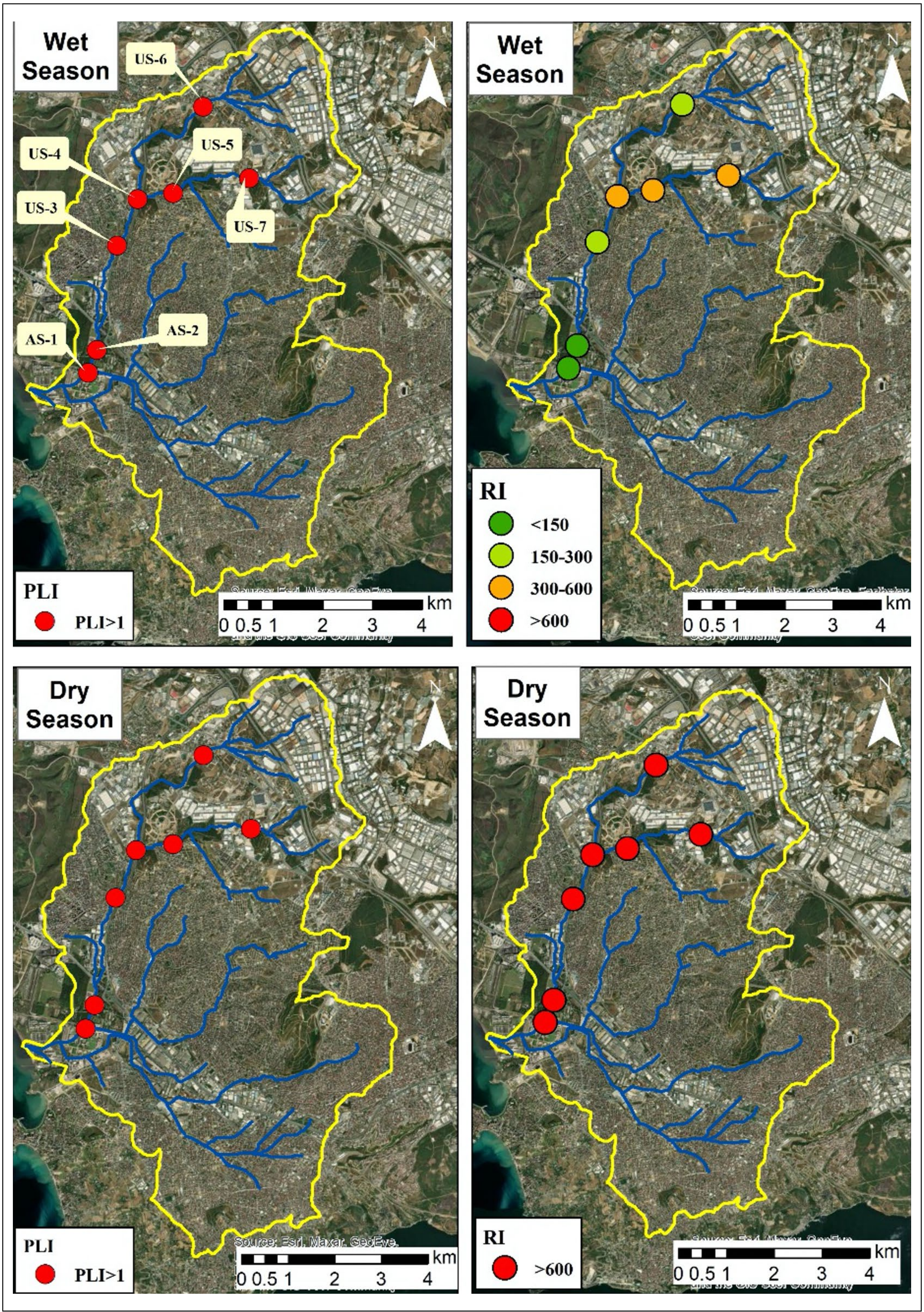

Figure 4. Spatial distribution of PLI and RI values of surface sediments collected during the dry and wet seasons.

acterization of sediment quality are essential for interpreting and quantifying the dynamic responses of these watersheds, ultimately aiding sustainable management practices.

This research evaluates the seasonal pollution levels of surface sediments in the Saz-Çayırova using various indices. The obtained results demonstrate variations depending on seasonality and the type of index employed. The RI was more consistent with EF and I-geo, revealing higher contamination levels during the dry season. The PLI analysis yielded more consistent results with EF and I-geo when evaluated on a station-by-station basis. The ranking of stations based on PLI values for the wet and dry seasons was US-4=US-7=US-3>US-6>AS-1>AS-2 and US-5>US-4>US-3=US-7>AS-2>US-6>AS-1, respectively. The RI values followed the order US-4>US-7>US-5>US-3>US-6>AS-2>AS-1 and US-3>AS-2>US-5>US-7>US-4>AS-1>US-6 for the wet and dry seasons, respectively. The EF and I-geo analyses showed comparable tendencies to the PLI analysis in both seasons. These finding suggest that RI analysis is more trustworthy for assessing temporal variations in the ecological risk of surface sediments, but PLI analysis gives a more consistent evaluation of spatial variations. The improved consistency of PLI in assessing spatial variations can be attributed to the inclusion of elements used in metal pollution indices like EF and I-geo. The better consistency of RI analysis in capturing seasonal differences stems from the flexible range of its scale compared to PLI analysis.

Future research should focus on modeling transport processes in addition to point-based monitoring of the sediment chemical composition. Studies incorporating computational approaches, particularly those addressing surface water-sediment and groundwater-sediment interactions, will provide crucial information for ecological risk assessment to decision-makers.

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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.

USE OF AI FOR WRITING ASSISTANCE

Not declared.

ETHICS

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

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Research Article

Numerical analysis of transient soil temperature variation during wildfires

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ABSTRACT

In this study, transient behavior of soil temperature during large forest fires is analyzed using the Comsol© software package. The increase in soil temperature during large wildfires can be very critical, especially when oil or gas pipelines have been laid at a certain depth in the soil mainly near forests. During forest fires, the temperature of the soil surface can reach extreme levels that penetrate deep into the ground if the fire is not extinguished within a short time. This increase in temperature on the soil surface can lead to extremely dangerous situations if the laying depth of the pipeline is not sufficient, as the heat conducted through the soil causes the surface temperature of the pipeline and therefore that of the fluid inside it to reach even high values. This can lead to a sudden rupture of the pipeline and ultimately lead to catastrophic consequences. The present study is conservative due to the assumptions made in structuring the numerical model. However, it is believed to provide invaluable information about the considerations in selecting gas pipeline locations and pipeline laying depths taking into account extreme temperatures due to wildfires. There is limited research on the topic regarding the time dependent conduction heat transfer through soils as a result of fires, but only in one dimension. Current study, being multi-dimensional, is therefore believed to be novel in the field. Future research could include extensive study on the energy content of different species of forest trees, considering their time-dependent heat release rates (HRR) during a forest fire, as well as experimental work if a field setup could be designed.

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INTRODUCTION

In recent decades, drastic climate changes have been observed due to global warming, caused primarily by ever-increasing concentrations of greenhouse gases and leading to unusual atmospheric phenomena such as extreme temperatures and drought [1]. These extreme temperatures coupled with low humidity pose a great risk of forest fires, especially in pine forests [2]. Once such fires start, they can spread over a large area in a short time and last for days until all the fuel (burning energy from living or dead biomass) is used up. As a result of these fires, dramatic consequences can occur such as loss of biodiversity as well as air pollution and deterioration of the physicochemical and biological properties of the soil. Currently, forecasting models based on fuel maps, remote sensing indices and statistical data can be used to predict the occurrence of wildfires [3]. A recent study evaluates the possibility of use of long time series, 30-m resolution fractional forest cover data obtained from satellites combined with multi-source data and integrated with multiple analysis methods [4]. Singh and Huang [5] used a machine learning approach to identify the role of climatic and anthropogenic factors in influencing fire probability and to map the spatial distribution of fire

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risk over a two-decade period. Climate change is having a strong impact on natural wildfire activity worldwide. For instance, naturally caused wildfires in the western United States have increased throughout history, particularly the southwest region has the highest wildfire activity under historical conditions [6]. Similarly, compared to other states in the northwestern Himalayas, Uttarakhand is the state with the highest risk of forest fires among Indian states. It is also shown that fires occur more frequently in the month of May and that evergreen coniferous forests burn more frequently among the forest types in this region, as shown by the analysis of forest fire hotspots based on radiation output, fire frequency and fire density [7]. Another example of using statistical data is to analyze the time series characteristics of forest fire distribution in Korea to understand that forest fire occurrence has long-term temporal correlations and to identify areas where the temporal irregularities of forest fire occurrence are consistent with local ones [8].

During wildfires, flame temperatures of up to 1500 K can cause the surface temperature of a pipeline located 10 m from the flames to reach temperatures of 900 K within 15 hours of the fire starting, which can lead to an increase in gas pressure that can result in bursting the pipeline [9]. Martinez et al. [10] performed a series of experiments and obtained ground surface temperatures between 570 K-2175 K during controlled fires and indicating this range of temperature can be observed in actual forest fires. This extreme surface temperature range can be explained by the fact that during forest fires the air temperature can reach values of up to 1600 K. During the thermal radiation heat transfer process, a significant part of the radiant power emitted by flames of up to 290 kW/m^2 is partly absorbed by the ground surface depending on the view (geometry) factor between tree and soil and absorption coefficient of the soil [11]. In an experimental study, similar temperature values, although with lower flux values, were observed as a result of conduction heat transfer occurring through the soil, thus requiring piping to be laid to a minimum allowable depth. Extreme ground temperatures are harmful because the primary cause of failures in gas pipelines is ruptures, especially in aging pipe materials, which require determining a safe installation depth [12].

In addition to the fire risk, other criteria also apply to determining the burial depth. To calculate pipeline burial depth as a function of pipe diameter, lateral earthquake forces may need to be used [13]. Likewise, traffic loads may need to be taken into account when determining the burial depths for different pipe diameters [14]. Another important factor in the severity of forest fires is the energy content, which varies between individual trees, as it determines the duration of burning and thus the peak temperatures that can be achieved during fires. The trees with the highest calorific value include various species of pine. Pine trees have various calorific values, which is released in a fire when the tree is completely burned [15]. For instance Pinus Sylvestris has an average calorific value of 21 MJ/kg. For such a pine tree with a trunk diameter of 27 cm and a height of 25 meters, this value can correspond to a total energy release of 20 GJ. Zeng et al. [16] provides similar figures in their research as 20.8 MJ/for coniferous species in Japan, 19.6–20.5 MJ/kg for 12 tree species grown under a short rotation forestry regime in New Zealand and 17.9–22.9 MJ/kg for indigenous mountain tree and shrub species of the northeastern Himalayan region in India. Burning time is also an important factor as it determines the peak values. Current study assumes that the radiation flux does not decrease over time. However, this is not the case in real fires, as energy release continues to decrease after the heat flux peak as the trees in a given region burn out over time. Temperatures during a wildfire peak sometime after the fire starts and then decline as the fire dies. Therefore, during a forest fire (simulated or real), the soil temperature varies accordingly as a function of time, both at the surface and at different depths in the forest floor [17]. Another factor that, in addition to surface heat flow, determines the intensity of heat diffusion through the soil is soil moisture. According to Preisler et al. [18] when soil is dry, higher temperatures are expected during forest fires due to the effect of humidity on the variation of soil temperature with depth and time. Similarly, another study evaluates the effects of soil water potential and soil water vapor under various soil, fuel, and fire conditions on forest floor temperature and concludes that soil moisture content during fire is crucial in understanding the fire effects on soil properties [19]. As discussed above, vegetation type is a critical factor in the intensity and severity of wildfires. Ground surface temperatures of up to 1260 K have been measured in aspen poplar forest fires, while temperatures in grass and shrub fires are in the range of 675–975 K [20]. In a more recent study, Fajković et al. [21] provides figures in the vicinity of 1350 K found in soil heating during forest fires. In addition to the total energy content, the energy released per unit of time, i.e. the heat release rate (HRR) of burning pine trees in forest fires, is also of crucial importance. However, HRR is greatly influenced by soil moisture content. According to a formula included in the study, a completely dry pine tree has an HRR of 344 kW/kg, while one with 25% moisture has 225 kW/kg, corresponding to a 35% reduction in heat output [22].

Pipelines as a whole, whether gas or general purpose pipelines, must be buried at a safe depth to prevent the risk of wildfires. A recent study examines a modeling method for assessing wildfire heat transfer through the ground to quantify whether the upper limit temperature for general supply operation pressure is exceeded during a wildfire [23]. According to the simulations presented in the study, the model found that the upper limit temperature for the operation pressure of the pipelines was exceeded at depths of up to 0.45 m, which provides a rough "minimum depth of pipeline burial depth" for many applications. Regardless of the cause of the pipe rupture, the most serious consequence of pipe failure is vapor cloud explosions, jet fires, and flash fires. Analysis of one study shows that the rate of serious incidents decreases as pipe diameter and wall thickness increase [24]. Three quarters of the serious incidents occurred in pipelines with relatively thin walls, in fact, a greater wall thickness could have prevented a large proportion of the incidents. Although increasing the thickness increases pipeline safety, this is often associated with higher material and installation costs. Thus, in addition to a safe burial depth and pipe wall thickness, the pipe material is also important.

The relevant literature mainly deals with aspects of the probability and severity of forest fires as well as the dependence of the consequences of fires on the maximum heat fluxes and the temperatures that occur, and there is only limited work on the time-dependent temperature penetration depth in forest soil. Equally important is the prediction of severity of such fires. Bayat and Yıldız [25] implemented different ML algorithms to forecast burned area size based on various characteristics such as temperature, wind, humidity and precipitation, using records of 512 wildfires that took place in a national park in Northern Portugal.

Analytical Model

The problem at hand is classified as "transient conduction in semi-infinite solids" because the soil surface is exposed to a certain heat flux (radiation) caused by the high temperature of the burning trees above while the heat is propagated throughout the soil. Solutions to this class of problems (transient conduction in semi-infinite solids) can be found in the heat transfer literature, where diagrams or exact analytical expressions such as Eq. (1) [26] and Eq. (2) [27] can be used. These equations apply to the case of constant surface heat flux q_o and constant surface temperature T_s, respectively. However, they do not correspond to the actual situation in a forest fire, as they provide solutions for the case where the surface area is infinite, as shown in Figure 1, while the temperature varies only with depth (z) and time (t). However, in the event of a forest fire, extreme heat flows can occur locally, which leads to heat diffusion not only into the depths but also horizontally on the planes, i.e. in x and y directions, with varying depths.

$$T(z,t) - T_i = \frac{2q_o(\alpha t/\pi)^{1/2}}{k} exp\left(\frac{-z^2}{4\alpha t}\right) - \frac{q_o z}{k} erfc\left(\frac{z}{2\sqrt{\alpha t}}\right) \quad (1)$$

$$\frac{T(z,t)-T_i}{T_i-T_s} = erfc\left(\frac{z}{2\sqrt{\alpha t}}\right) \quad (2)$$

Convection at the surface is neglected because the main mode of heat transfer is radiation, as the magnitude of radiation is much larger. Furthermore, the middle of the forest can be viewed as an enclosure surrounded by trees, where small temperature differences between the ground surface and the surrounding air do not justify the inclusion of convection, which would otherwise have a cooling effect on the ground surface. To illustrate the behavior of soil temperature under constant surface heat flux and constant surface temperature boundary conditions, temperatures for different soil depths are plotted against time using the above equations, as shown in Figure 2. Since the temperature variation becomes negligible below 0.5 m, they are plotted between 0 and 0.4 meters. On the other hand, as can be seen in the constant heat flux graph, temperatures rise indefinitely, suggesting that the constant surface heat flux model is inappropriate. Therefore, a constant surface temperature model is used.

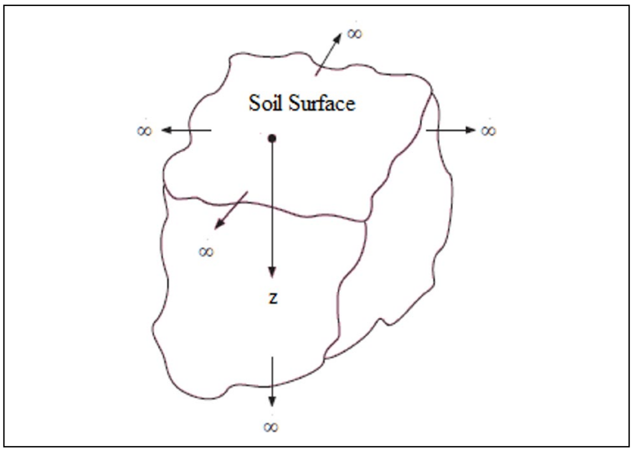

Figure 1. Analytical model (Adapted from Çengel [27]).

Numerical Model

The numerical method is implemented using the Comsol© software package. Analyzing heat transfer by conduction, convection and radiation with the Heat Transfer Module, an add-on product to the COMSOL Multiphysics® simulation platform, makes it possible to find solutions to problems that might otherwise be too complicated to solve analytically. The Heat Transfer Module includes a comprehensive set of features for studying thermal designs and effects of heat loads. For instance, temperature fields and heat flows in components, housings and buildings can be modeled using this module. To virtually examine the real-world behavior of a system or design, multiple physical effects can be easily coupled into one simulation using the multi-physics modeling capabilities included in the software. All functions of the heat transfer module are based on the three types of heat transfer: conduction, convection and radiation. The thermal conductivity of each material can have isotropic or anisotropic thermal conductivity and can be constant or temperature dependent. Convection, the flow of fluids in heat transfer simulations, can be forced or free (natural) convection. Thermal radiation can be accounted for by surface-to-surface radiation or by radiation in semi-transparent media. There are many variations within the types of heat transfer, and the different types must be considered together; in some cases all three at the same time. All of this requires different equations to be processed simultaneously to ensure accurate models.

The first step for the numerical model is to create the geometry for the computational domain. However, due to the fact that during a forest fire there can be localized extreme heat flows, leading to heat diffusion not only to the depth, but also to the surface and to planes parallel to the surface, the problem becomes a three-dimensional problem with $T=f(x,y,z,t)$. The computational domain is 5x5 m at the surface and 1 m at depth. A 3x3 m area is assumed to be exposed to a constant temperature only on the soil surface (Fig. 3) to represent the local radiant energy absorbed by the soil, which is equivalent to the projection area under a burning tree. Selection of the shape of the projected area and the ratio of the projected area to the upper surface of the domain are considered to be unimportant as crown size

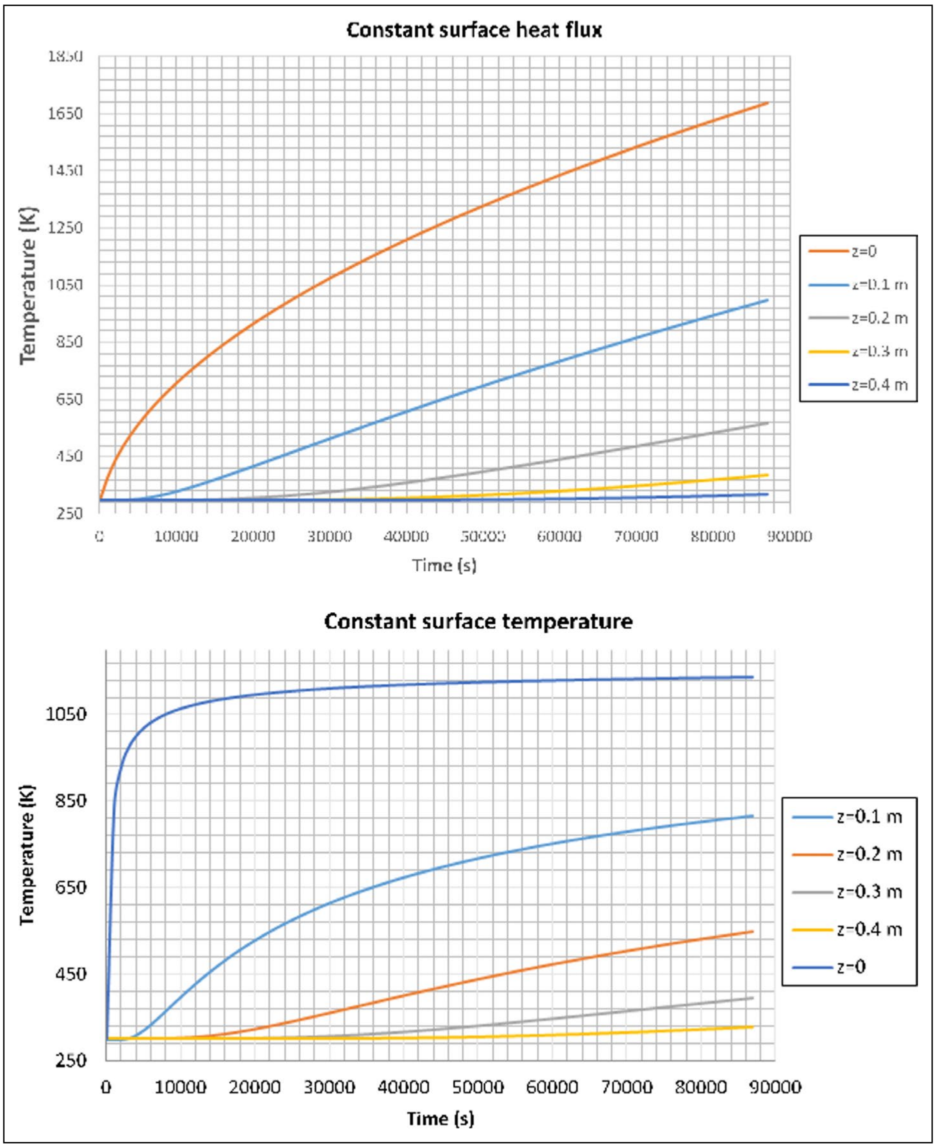

Figure 2. Temperature variation of soil for two different surface boundary conditions.

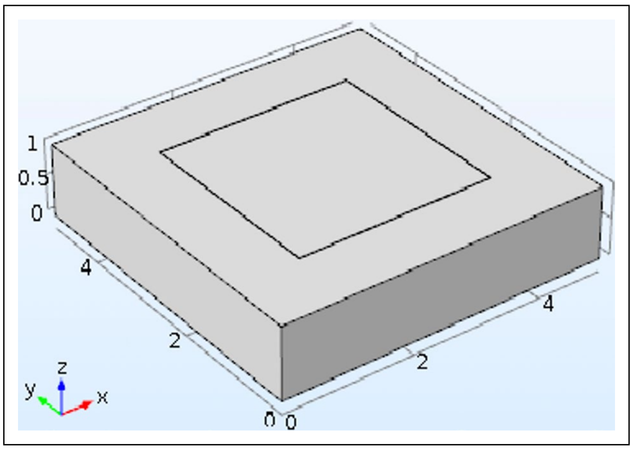

Figure 3. Geometry of the numerical model (5x5 m domain).

and height of trees are highly diversified, therefore an assumption had to be made. It should be noted that the surface of the numerical model has *z=1* m, while the surface in the analytical model has *z=0* m.

The second step is to create a mesh for the computational domain. Mesh size and type, i.e. the number of grid elements, determine the accuracy of the results as well as the execution time and memory usage. The calculations were optimized through a series of trials until the solutions became invariant. "*Physics controlled mesh*" with "*fine mesh*" element size is chosen as the meshing algorithm. *The unstructured mesh structure* in Figure 4 (top) has 152,725 DOFs for the domain shown, the majority of which is *tetrahedral*, plus 58,496 internal DOFs. The middle section of the domain contains much finer elements because temperature gradients are expected to be much higher in this region. To evaluate the grid dependence of the problem at hand, the single tree domain is meshed with an "*extremely fine mesh*" as shown in Figure 4 (below), with the number of mesh elements increased by 24 times and the computation time increased by 4 times, similar to those of "*Fine Mesh*" even though the storage allocation only increased by 30%. On the other hand, when the solutions of two different mesh sizes are compared, one finds that there is no

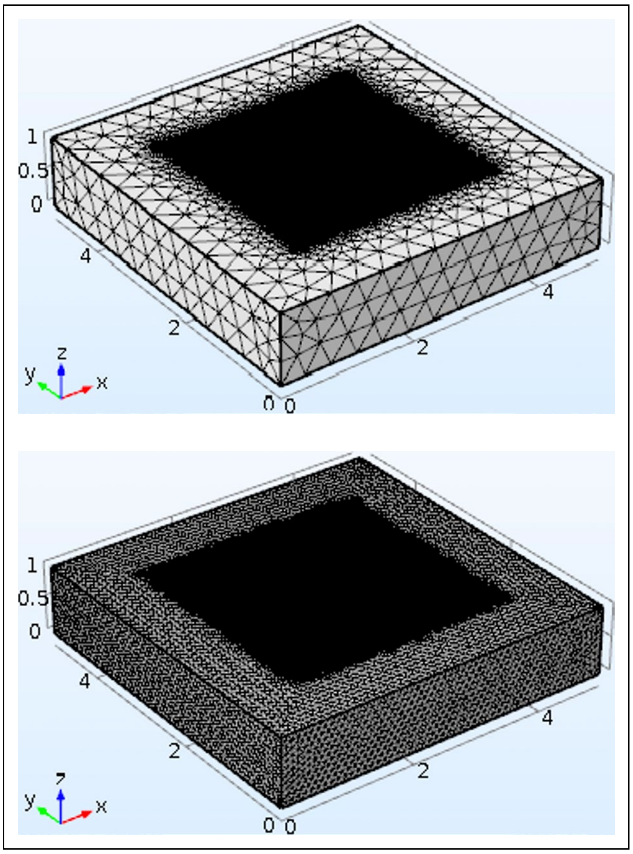

Figure 4. Mesh structures of the model (5x5 m domain). Top: "*Fine Mesh*", Bottom: "*Extremely Fine Mesh*".

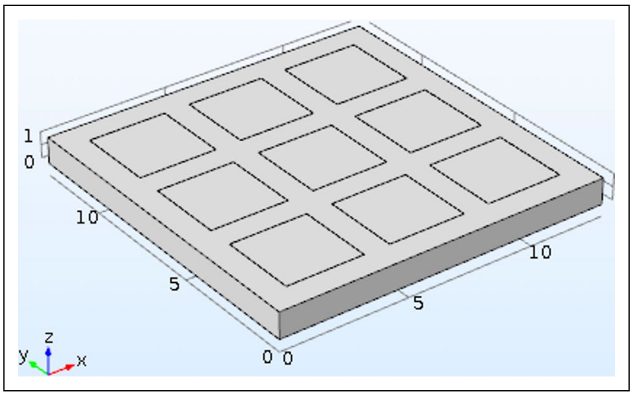

Figure 5. Geometry of the numerical model (16x16 m domain).

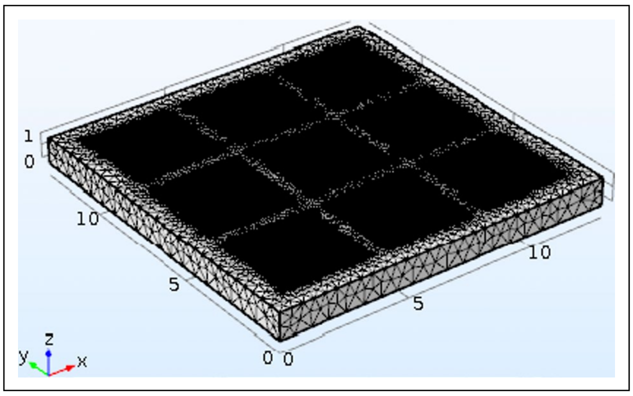

Figure 6. Mesh structure of the model (16x16 m domain).

noticeable difference, suggesting that the solution is mesh independent, provided the mesh size is fine enough for the problem at hand. Therefore, using a finer mesh than the one used in this work will only result in a waste of computing resources and a much longer running time.

When setting up the model, the software package assumes the following differential equations to solve the transient problem:

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \mathbf{u} \cdot \nabla T + \nabla \cdot \mathbf{q} = Q \qquad (3)$$

$$\mathbf{q} = -k\nabla T \qquad (4)$$

where **u** and **q** are velocity and heat flux vectors, respectively. However, since there is no flow in the domain, **u**=0.

The boundary and initial conditions are 900 °C (for a 3x3 m portion of the domain) and 27 °C (at other locations), respectively. It is assumed that the 3x3 m^2 area is suddenly exposed to the initial condition, which is not the case in an actual fire.

Soil properties are selected from the package's built-in material database. The properties vary with temperature in the numerical solution, while they are usually assumed to be constant in the analytical solution. This is an important feature of the package, apart from the three-dimensionality of the numerical method, as there can be significant variations in properties with temperature: thermal conductivity, specific heat and thermal diffusivity are all piecewise polynomial functions of temperature. As an example, the variation of thermal diffusion coefficient with temperature is

$$\alpha = 1.81x10^{-7} - 6.00x10^{-10}T + 8.89x10^{-13}T^2 - 4.01x10^{-16}T^3 \qquad (5)$$

Equations 3, 4 and 5 are from the Comsol© documentation published on their website. The density of the soil is assumed to be constant (2000 kg/m^3). It is obvious that the solutions for other types of soil may lead to different results. However, if the data on the thermal properties of the soil is available, the solution can be updated accordingly. As an example, Makarychev and Bolotov [28] provide thermophysical properties of different soil types. According to the authors, depending on the humus content, bulk density of the soil varies between 1320–1380 kg/m^3 while specific heats and thermal conductivities vary between 979-1091 J/kg.K and 0.22–0.388 W/m.K, respectively, corresponding to a thermal diffusivity variation of $1.5x10^{-6}$-$3x10^{-6}$ m^2/s. Above equation also provides a similar thermal diffusivity range at a temperature range of 0–150 °C.

To examine the validity of the assumption for the 5x5 m domain, a larger 16x16 m domain accommodating an array of 3x3 trees is also examined, as shown in Figure 5. Figure 6 shows the mesh structure of this larger domain with more than 1,405,906 DOFs plus 495,136 internal DOFs have been solved.

RESULTS AND DISCUSSION

The total computation took 12 minutes for the first setup to converge and 58 minutes for the second setup, when "*Fine Mesh*" grid size is used. The temperatures for the middle of the region (*2.5,2.5,z*) of the first setup, where they are high-

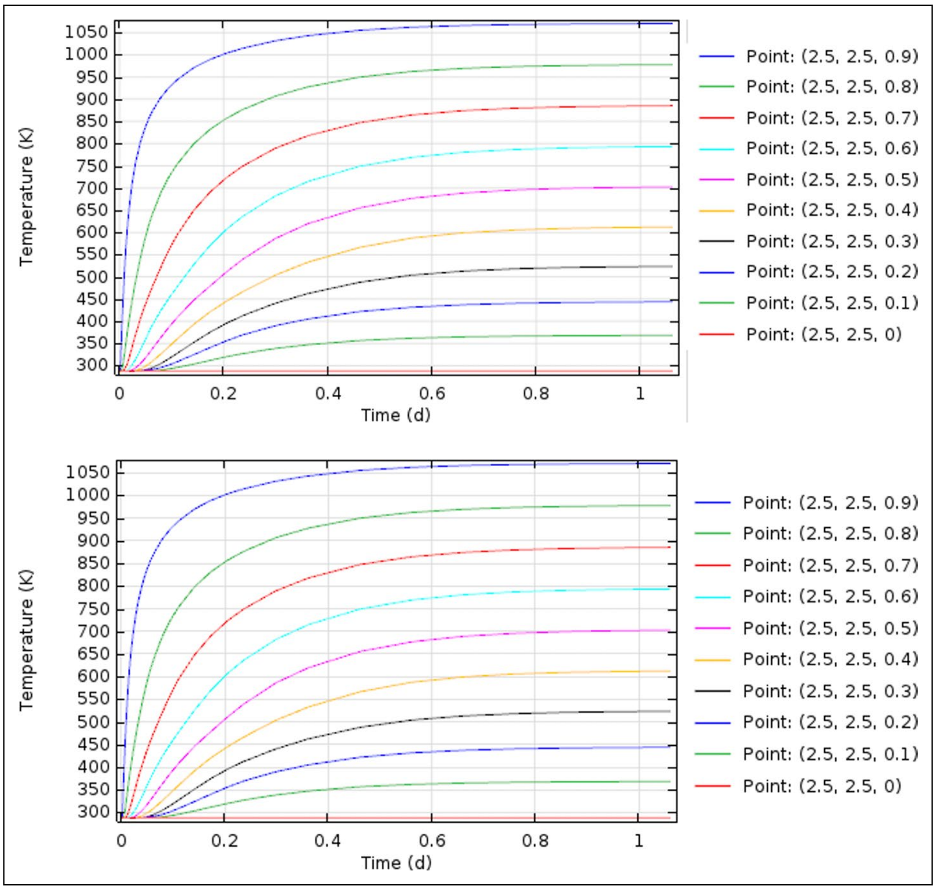

Figure 7. Temperature vs. time for 5x5 m domain. Top: "*Fine Mesh*" Bottom: "*Extremely Fine Mesh*".

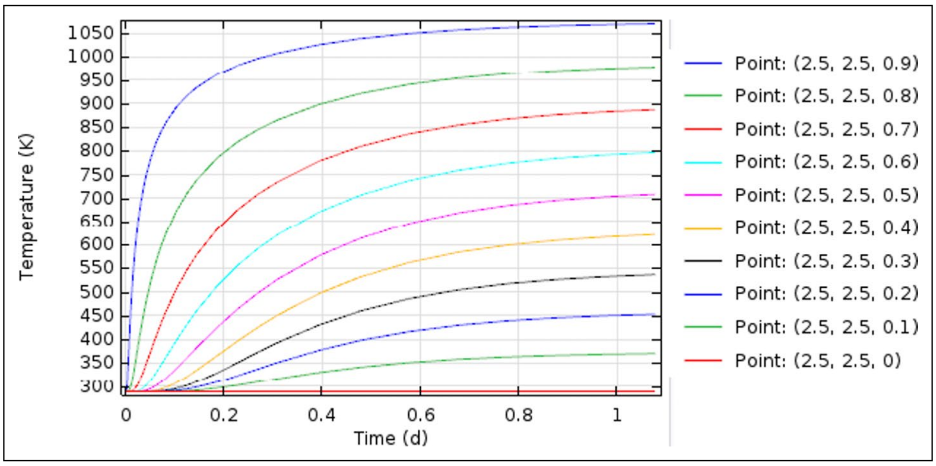

Figure 8. Temperature vs. time for 16x16 m domain.

est at each location parallel to the (*x,y*) plane, are plotted against time as decimal fractions of a day. It should be noted that the surface in the solution corresponds to *z=1 m*, while at the bottom of the domain *z=0 m*. Temperature vs. time for different mesh sizes is shown in Figure 7 (top and bottom), where temperatures peak and level off about halfway through the day. As can be seen from Figure 7, the *Fine Mesh* and *Extremely Fine Mesh* solutions are exactly the same.

These graphs suggest that with the specified soil properties, temperatures at locations deeper than 1 meter are below 300 K and therefore there is no danger to the pipeline. However, even at half depth *(z=0.5 m*), temperatures can be so high that the *pressure* in the gas pipeline can reach a value twice the original value, indicating the possibility of rupture due to increased *hoop stress* as well. The resulting weakening of the pipe material due to increased temperatures leads to a *reduced yield strength*. Petroleum pipelines could also face a similar risk in wildfires, depending on the temperature and thermal expansion of the fluid.

As shown in Figure 8, it is observed that the mean temperatures of the projections of each of the 9 trees in the 16x16 m area are similar to those in the 5x5 m domain. The small

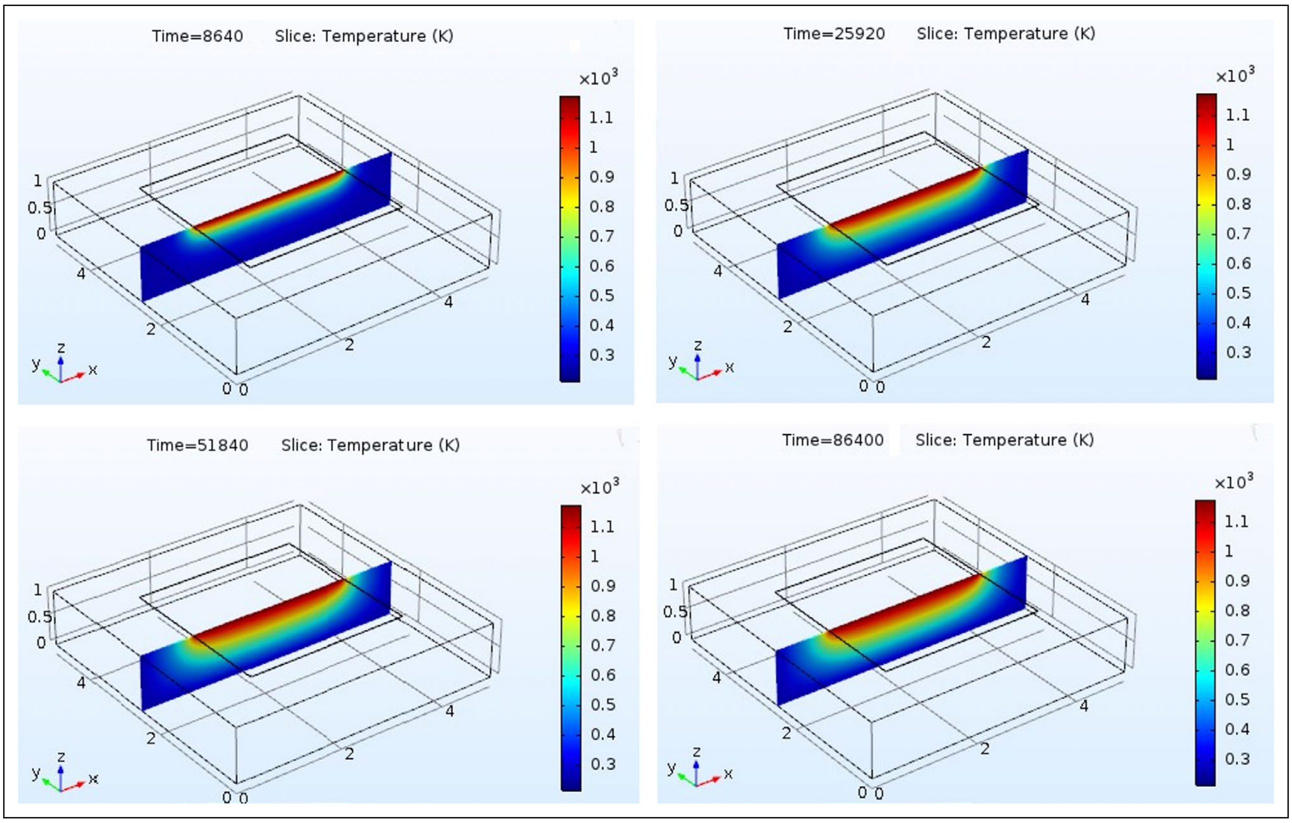

Figure 9. 2-D temperature contour plots on (*x,z*) plane for 5x5 m domain for different times (in seconds) of the day.

differences between the two cases arise from the fact that the single tree domain extends in the x and y directions on horizontal planes (*x,y*) to infinity, where the temperature approaches the initial temperature. On the other hand, the temperature gradients in horizontal planes of the 3x3 tree domain are influenced by the neighboring trees. This is why a 3x3 layout of a given depth takes more time to reach a specific temperature than a single tree, because of the much smaller temperature gradients in *x* and *y* directions, i.e. $\partial T/\partial x$ and $\partial T/\partial y$.

It is also interesting to look at the temperature variation as temperature contours. Figure 9 shows the temperature distribution on a section representing the vertical (*x,z*) plane for different times of the day and Figure 10 in three dimensions at the end of the day.

Both 2D and 3D plots suggest that heat diffuses not only in depth but also in horizontal directions, proving the inappropriateness of the analytical solution given in Equation 1 due to the fact that it is one-dimensional. As shown in Figures 11 and 12, it can be observed that the temperature contours of the projections of each of the 9 trees in the 16x16 m area are also similar to those in the 5x5 m area.

In Figures 9 and 11, it is aimed to provide time dependent temperature distributions in *x* and *z* directions on (*x,z*) plane only as they are same as those in *y* and *z* directions on (*y,z*) plane. On the other hand, time dependent temperature distributions in Figures 10 and 12, temperature distributions are three-dimensional.

The aim of this study is to estimate variations in soil temperature with soil depth due to wildfires, particularly in lo-

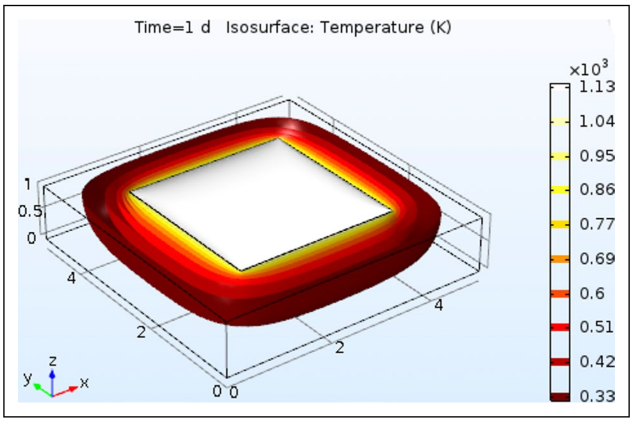

Figure 10. 3-D temperature contour plot for 5x5 m domain (day end).

cations where oil or gas pipelines run in or near forests. The distribution of temperature over soil depth is essential for determining the minimum laying depth of pipes in order to reduce the hazards that may arise from increased surface temperatures of pipes due to heat diffusion through the soil. To prevent catastrophic events, it is important to bury pipelines at a safe depth. Unburied natural gas pipelines can be at great risk due to elevated pipeline surface temperatures during drought-related wildfires due to radiant heat given off by the flames of burning trees. The temperature distributions obtained in this study were compared with those in the publication by Richter et al. [23]. They assume surface heat fluxes of 15–30 kW/m^2 for wild fires in residential areas. According to their study, at 0.1 m depth, the soil tem-

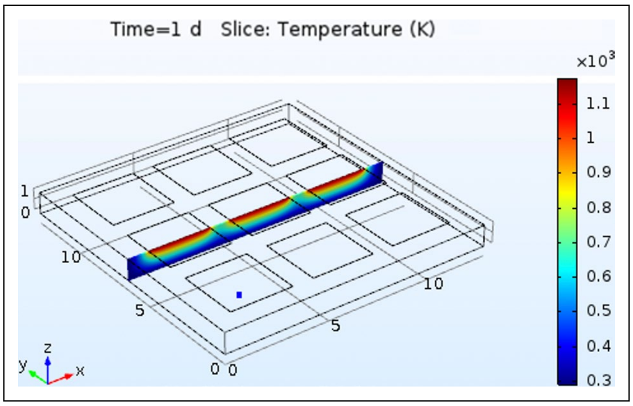

Figure 11. 2-D temperature contour plots on (x,z) plane for 16x16 m domain (day end).

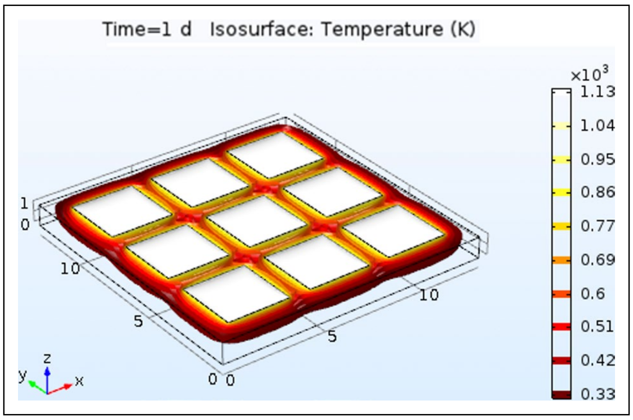

Figure 12. 3-D temperature contour plot for 16x16 m domain (day end).

perature reaches 675 K in 2 hours at 25 kW/m^2 for which the surface temperature is 2175 K as in this study, while the soil temperature is 700 K at the same depth and time in this study. This small difference between these values of the two studies is attributed to the differences between two analyses: in the work with which this study is compared, a one-dimensional analysis was considered and the soil properties are constant, while in this study, the computational domain is three-dimensional and the soil properties are temperature dependent.

The heat flux value of 25 kW/m^2 in the case of a tree fire can be justified as follows: assuming a tree crown diameter and trunk height of 3 m and 8 m, respectively, a geometry factor of F_{tg}=0.12 between the tree top and its projection is found using the graph for "View factor between two coaxial parallel disks". Radiation exchange between two surfaces can then be determined as given in Equation 6 [20]:

$$q=\varepsilon F_{tg}\sigma(T_t^4-T_g^4) \qquad (6)$$

where ε is emissivity factor, F_{tg} view (geometry) factor between the projection area (circle) of the crown and the ground, σ Stefan-Boltzmann coefficient and T_t and T_g are burning tree and ground temperatures, respectively. Using a rough value of ε=0.85, q can be calculated as 25 kW/m^2 using burning tree and ground temperatures of 1275 K and 1275 K, respectively, as mentioned in the introduction section.

By closely examining 2D and 3D solutions, the following results were drawn:

1. Under the assumed initial and boundary conditions, soil temperatures tend to level off or reach a quasi-steady state in about half a day, assuming that ground surface temperature boundary conditions remain constant. However, this is not the case in a real fire, as explained in the conclusions section.
2. Since the thermal properties of the soil come from the software's material database, solutions suggest that the minimum laying depth of natural gas or petroleum pipelines is 1 meter to prevent excessive pipe surface temperatures.
3. One-dimensional analytical solutions proposed in the literature are not suitable for this class of problems because the problem at hand is actually three-dimensional.
4. If the data on the thermal properties of the soil is available, it is important to update the solution accordingly, as the solution may give a completely different temperature distribution as a function of space and time.

CONCLUSION

This numerical study investigates spatial and temporal temperature variations in the soil during wildfires. If the site is near a forest or in a forest, the depth of laying the pipeline is particularly important because heat penetration into the ground during forest fires is closely related to one of the soil properties, thermal diffusivity, which can be significantly different in different areas can soil types. It is then important to comprehensively examine the soil properties and determine the laying depth of the pipeline accordingly. Future work could include extensive work considering time-dependent HRR of different species of forest trees during a forest fire. The transient heat released is transferred as convection to the environment above the forest, as radiation to the sky, and also as radiation to the ground beneath the trees. The last part of the released heat is absorbed by the soil, which leads to temporal variations in the soil surface temperature and thus to transient heat conduction in the soil. Apart from the variation in HRR, various tree species have different calorific values when they are completely burned. As a result of this, the rate of radiant energy and the total energy absorbed and stored by the soil during fired will be different. The new study, therefore, aims to provide more realistic temperature distributions in the soil by using tree burn data. However, although conservative, the present study also provides invaluable information in terms of preliminary considerations when selecting gas pipeline locations, as well as calculations of burial depths that take into account extreme temperatures due to wildfires. Another future direction of study could be to conduct a series of experiments with different surface heat fluxes and soil types aimed at measuring the variation of soil temperature with depth and time, although the design of the experimental setup could prove challenging due to physical constraints and power inputs taken into account if realistic results are to be derived from the experimental data.

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.

USE OF AI FOR WRITING ASSISTANCE

Not declared.

ETHICS

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

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Review Article

Revisiting e-waste management: A review of global practices and sustainability

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ABSTRACT

With rapid population growth, as well as, technological advancement, the generation of e-wastes is increasing day by day and has become a fact of emergent concern for scientific and research communities worldwide. Though the most developed territories generate the highest amount of e-wastes, little efforts has been put towards managing them. European countries, including United Kingdom, Germany, and France are managing significant amount of e-wastes responsibly. The informal and unscientific management of e-wastes led to severe health and environmental hazards. The traditional waste management methods, such as, landfilling, and incineration expels significant amount of heavy and toxic chemicals to the environment, leading to severe air, water, and soil pollution. However, proper management strategies for e-wastes not only inhibit the associated harmful effect towards the lives on earth, but also favor circular economy. The sustainability of the strategies for managing e-wastes lie in the responsibility of all stakeholders associated with it. In this review, we have discussed the statistics of global of e-wastes generation and recycling, effect of e-wastes towards lives and the environment, different methodologies of managing e-wastes, and strategies for sustainable e-waste management.

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INTRODUCTION

The rapidly growing population, as well as, modern civilization have revealed a new problem to the environmental and scientific community owing to the disposal of electronic gadgets. A wide range of devices, including consumer electronic e-waste, such as, TV, light, microwave, smart watch, remote control etc. and information communication e-waste, consisting of smartphone, laptop, cellphone, computer etc. can be considered in the category of e-wastes [1, 2]. Problem arises when these electronic wastes are either broken or discarded after use. The rapid industrial and technological advancement in the global scenario have also increased the amount of e-wastes in each year [3]. The inappropriate and unscientific disposal of this waste is not only unprofitable in economic aspect but also detrimental towards lives on earth as it led to several toxic chemicals to the environment [4]. Moreover, with advancements in electronics and modern technologies the lifespan of electronic goods has been decreased substantially. As a result, the electronic wastes increased proportionally with technological modernization. The US Environmental Protection Agency (US EPA) survey suggests an average disposal of 125 million mobile phone each year [5].

Developed, as well as, developing territories like, China, USA, India, Japan etc. generates highest amount of e-wastes in the global scenario [6]. In 2022, the global electronic waste

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generation has reached 57.4 Mt with an average rise of 2 Mt in each year [7]. Out of the total e-wastes collected, only 17.4% are being properly recycled. The e-waste generation is projected to be 74.7 Mt in 2030 [8]. India contributes appreciably good amount of e-wastes in worldwide e-waste generation. The sources of e-wastes constitutes of several types viz., governmental (15%), household (15%), Private (33%) & public (23%). So to manage this high amount of e-wastes policies, principles, complex process should come in operation [9].

E-waste is contains several metals and non-metals as its constituents which make the process of management unique as well as diversified. Typically, the composition of e-waste contains different chemical entities, viz. organic compounds (~30%, e.g., polymers, flame retardant), ceramic materials (~30%, e.g., silica, alumina, mica), and inorganic compounds (~40%, e.g., ferrous and non-ferrous metals). The inorganic part of the waste contain base metals like aluminium, iron, tin, copper etc., noble metals like palladium, silver, gold, etc., heavy toxic metals like, cadmium, nickel, chromium, zinc, mercury, beryllium, lead etc., and rare earth metals like, gallium, tantalum etc. [10]. The existence of toxic hazardous chemicals, such as, mercury, cadmium, lead, chromium (VI), and different brominated flame retardants are responsible in making the management process difficult. In printing circuit boards (PCBs) significant amount of lead is found to be present in addition to copper. These metals are also responsible for environmental and health hazards in the form of liquid crystals in LCDs [11, 12]. The advancement of technologies and advanced features in the smartphones have significantly enhanced the amount of nickel, copper, silver, barium etc. [13]. The improper management of the hazards present in the e-wastes negatively impacts health and environment. In India, the lack of infrastructure and government initiatives for recycling have limited the utilization of e-wastes into useful products and evoked traditional disposal techniques for solid wastes, like, open dumping, land filling, and incineration. These methods are not only economically non-viable but also led to severe air, water and soil pollution [14].

Easy disposal methods, such as, open burning, acid wash, incineration are adopted by countries like India, and China for managing electronic wastes as these methods are easy and economically viable. However, advanced companies like, Noranda, Cimelia, Unicore are following different sophisticated methods, such as, pyro metallurgical, electrochemical, hydrometallurgical technique for recovering non-ferrous metals and utilize them in electronic equipment industry [15, 16]. European territory is doing appreciably good in recycling e-wastes and making useful products and thus saving lives, as well as, environment very effectively. Asian countries are found to be suffered from unmanaged accumulation of e wastes. To reduce waste generation effort should be put in the utilization of different parts of the electronic equipment in some other equipment. This sort of refurbishment will not only help to reduce the cost of the material, but also help to reduce hazards associated with the disposal of the equipment. Small chip level industry could be constructed for refurbishing electronic goods and make them usable [17]. The proper management of e-wastes can only be done by policies from the superior authorities, segregation of the wastes collected and proper research and developments in the field of e-waste management. Not only government initiatives, but also efforts from different non-government organizations, local bodies and most importantly people should come into force to recycle and manage e-wastes and get rid of hazards associated with e-wastes [15].

The prime goal of this review is to investigate the global status of e-waste management and research going worldwide on e-waste management. The evil effects of unscientific disposal of e-wastes on lives on earth and environment have well been explored. In addition, the traditional and systematic procedures of e-waste management can be found in the present review. The utilization of formal and sustainable strategies of e-waste management can led to circular economy. Moreover, several sustainable development goals (SDGs) can be achieved associated with proper scientific disposal of e-waste management.

MATERIALS AND METHODS

This review considers the data published on e-waste management during the span of last twenty years using a distinctive search string in the Web of Science database. The search string in the present investigations was “TS=((((e-waste) OR (electronic waste) AND management))) in the 'Advanced Search' of WoS database for the period 01-01-2004 to 31-12-2023 i.e., last twenty years. This database has proved itself as very much effective in bibliometric analysis as it led to most relevant results. Total 5486 publications were resulted which includes articles, reviews, conference proceedings etc.

Here, the Bibiometrix-Biblioshiny package of R has been employed to quantitatively analyze the bibliometric parameters associated with the e-waste management research [18]. This statistical tool facilitates the growth of the e-waste management research executed by the top five countries. The mostly used keywords, as well as, the sources with average citations per publication (ACPP) have also been studied using this tool.

Global Status of E-Waste Management

Figure 1 depicts different statistical parameters related to e-waste management. As can be observed, the electronic wastes increases in each year and have reached 59.4 Mt. The total electronic waste is projected to be 74.7 Mt in 2030. The continent wise total e-waste generation and per capita waste generation has been depicted in Figure 1b. Although, Asia generated the highest amount of electronic wastes, the per capita electronic waste generation was found to be highest in Oceania. The sources of electronic wastes have been depicted in Figure 1c. As can be seen, small equipment generates highest wastes (32.5%) followed by large equipment (24.4%), temperature exchange equipment (20.1%), screens and monitors (12.5%) and

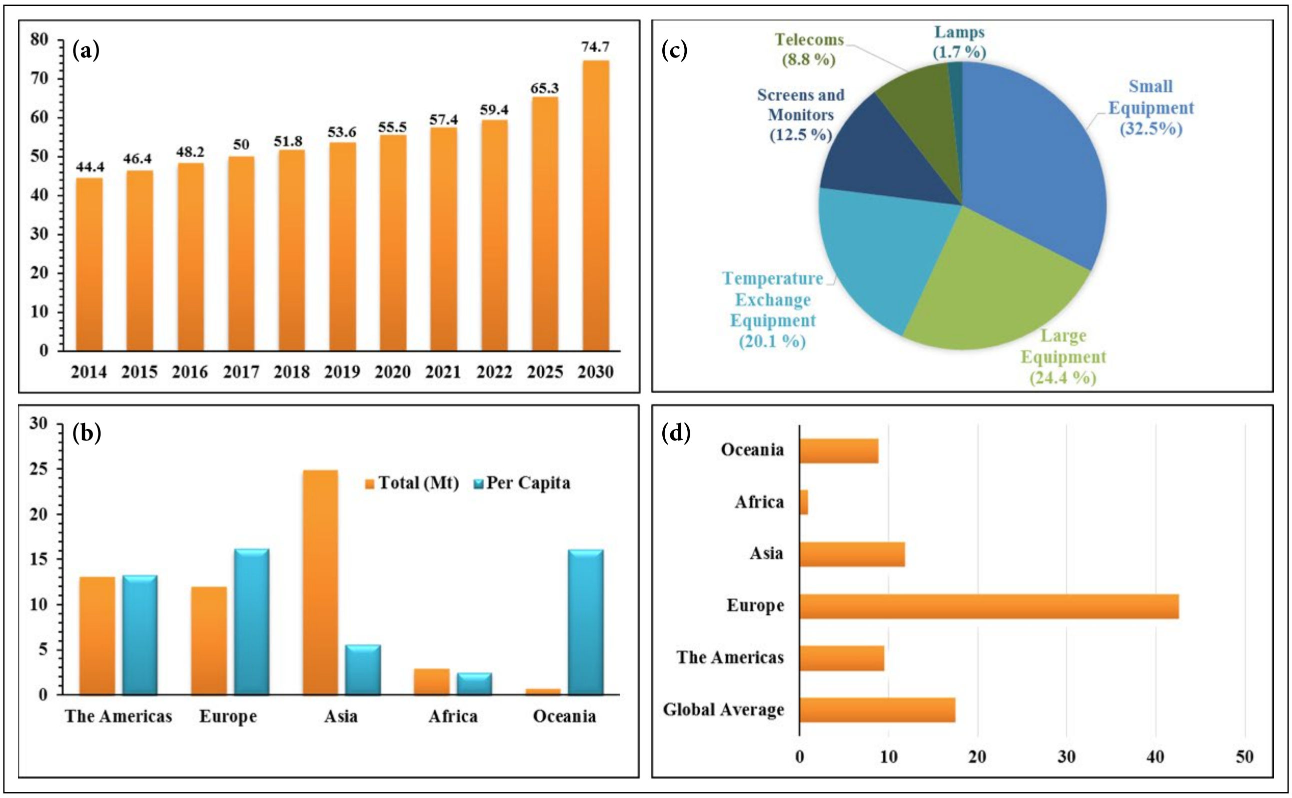

Figure 1. **(a)** Year wise growth in the global electronic waste generation (Mt) with future forecast, **(b)** Total electronic waste generation (Mt) and per capita e-waste generation in different continents of the world, **(c)** Different sources of global electronic waste materials, **(d)** E-waste recycling rate by different continents. Data collected from [19].

Table 1. Country-wise total electronic waste production and rate of recycling [8]

Serial number	Country	E-waste produced (Kt)	Recycling rate
1	China	10129	16%
2	USA	6918	15%
3	India	3230	1%
4	Japan	2569	22%
5	Brazil	2143	0%
6	Russia	1631	6%
7	Indonesia	1618	n/a
8	Germany	1607	52%
9	UK	1598	57%
10	France	1362	56%

telecoms (8.8%). The rate of recycling was found to be highest in Europe (42.5%) as can be observed in Figure 1d.

Table 1 depicts the top 10 countries collecting highest amount of e-wastes and rate of recycling out of the total e-wastes collected. European countries, like, Germany, UK, France were found to possess highest rate of recycling. China produced the highest e-wastes (10129 Kt) with significantly low rate of recycling (16%). India, Brazil, Indonesia was found to recycle at a significantly lower rate (<1%) and found to contribute very poor performance in terms of e-waste management and recycling.

Global Status of E-Waste Management Research

The global status of e-waste management research has been compared in terms of year-wise growth in the number of publications, country-wise production of publications along with year-wise growth, frequency of most used keywords, and journal-wise distribution. The statistical data related to the e-waste management, as revealed from the Bibliometrix-Biblioshiny, has been summarized in Table 2. As evident from the table, the total 5486 documents were published in 1048 sources, which includes journals, conference proceedings, books etc. The annual growth rate is found to be 7.66, suggesting growing interest of research community towards managing e-wastes. The average citation per document (32.21) depicts high acceptability of the documents towards global research communities involving in e-waste management research. The statistical analysis also predicts 7452 keywords in keywords plus and 10957 author's keywords suggesting a wide area covering by e-waste management. On analysing the number of authors, total 13582 authors are found to be authored the documents published on the present topic with the co-authors per document 4.81. It is worthy to mention that the international co-authorship as 29.3%, suggesting appreciably good inter-country collaboration in managing e-wastes. Moreover, the total 5486 documents, published during the twenty years span, includes 4207 articles, 553 review papers. The evaluation of the statistical data on e-waste management suggests the enhanced interest of global community, mention-worthy inter-country collaboration, and versatility of the present topic.

Table 2. Statistical data of the articles published on e-waste management during the last two decades

Description	Results
Main information about data	
Timespan	2004:2024
Sources (journals, books, etc)	1048
Documents	5486
Annual growth rate %	7.66
Document average age	5.89
Average citations per doc	32.21
References	167598
Document contents	
Keywords plus (ID)	7452
Author's keywords (DE)	10957
Authors	
Authors	13582
Authors of single-authored docs	249
Authors collaboration	
Single-authored docs	311
Co-authors per doc	4.81
International co-authorships %	29.3
Document types	
Article	3187
Article; early access	1220
Review	467
Review; early access	286
Others	326

Year-wise Growth in the Number of Publications

Figure 2a depicts the year-wise growth in the number of publications on e-waste management during the span of last 20 years (2004–2023). As can be seen the number of publications were increased with time suggesting enhanced interest of global community towards e-waste management research. If the total twenty years (2003–2022) is divided into four periods of five years, the last period (2018–2022) is found to publish highest number of articles (3077) out of the total (5486) publications. The second last period (2013–2017) followed the last period and 1557 number of articles were published in this period. The year-wise growth in the number of publications suggests an increase in the number of publications on e-waste management in subsequent years. This data suggests the concern of the global community in developing new strategies and processes for managing e-wastes for the sustainability of the environment.

Country-wise Production and Year-wise Growth of Articles

The most productive countries (top ten) in publishing research articles in the field of e-waste management are depicted in the world map in Figure 2b. The data was collected in terms of the designation of the corresponding author. It is mention-worthy that, the highest number of articles (1934) on e-waste management was published from China. This was followed by USA (711) and India (583) publishing appreciably good number of articles in the said field. Other countries with appreciably good number of publications on e-waste management are Australia (287), UK (275), Canada (219), Italy (208), and Germany (188). The distribution of the present research topic among different countries suggests significant research activities around the globe.

Figure 2c depicts the year-wise growth of the e-waste management research executed by the top five countries. It is worthy to mention that the initial five years of research on e-waste management lies in an almost linear zone suggesting very less research focus during 2004–2009. After 2009, the slope of the line readily increases being highest for China. The dominancy in the e-waste management research executed by the authors from China in the entire period considered in this study is well evident from this analysis. This trend was followed by USA and India in the plot representing year-wise growth of number of articles.

Frequency of Mostly Used Keywords

The frequency of keywords (top twenty) used in the present topic is summarized in Figure 3a. As can be seen, 'management' is the most frequently used keywords followed by 'recovery', polybrominated diphenyl ethers', 'electronic waste', 'e-waste' etc. The other keywords with mentionable presence in the articles on e-waste management are 'heavy-metals', 'printed-circuit boards', 'metals', 'brominated flame retardants' etc. The frequency of keywords suggest the association of the present topic with waste management, more specifically solid waste management, environmental and human impact of e-waste and sustainable development of the environment.

Journal-wise Distribution of Articles

The number of articles published in different journals (top ten) on the said topic has been summarized in Figure 3b. It is mention-worthy that, 'Waste management' published highest number of articles (~271) in the field of e-waste management. This was followed by 'Journal of cleaner production' 'Science of the total environment', 'Environmental science and pollution research', 'Resources conservation and recycling', publishing appreciably good number articles in the field of e-waste management. The distribution of journals suggests publication of the e-waste management papers specifically in the field of waste management and environmental science. Moreover, most of the journals publishing articles on e-waste management are of good quality, Q1 journals of international repute.

The average citation per publication (ACPP), an important tool to establish acceptability of the article by the worldwide scientific community has also been depicted in Figure 3b. As can be seen, the ACPP gets maximized for 'Environmental science and technology' suggesting highest citations received by the articles published in the said journal during this time span. This was followed by 'Environmental international', 'Resources conservation and recycling' and 'Waste management'.

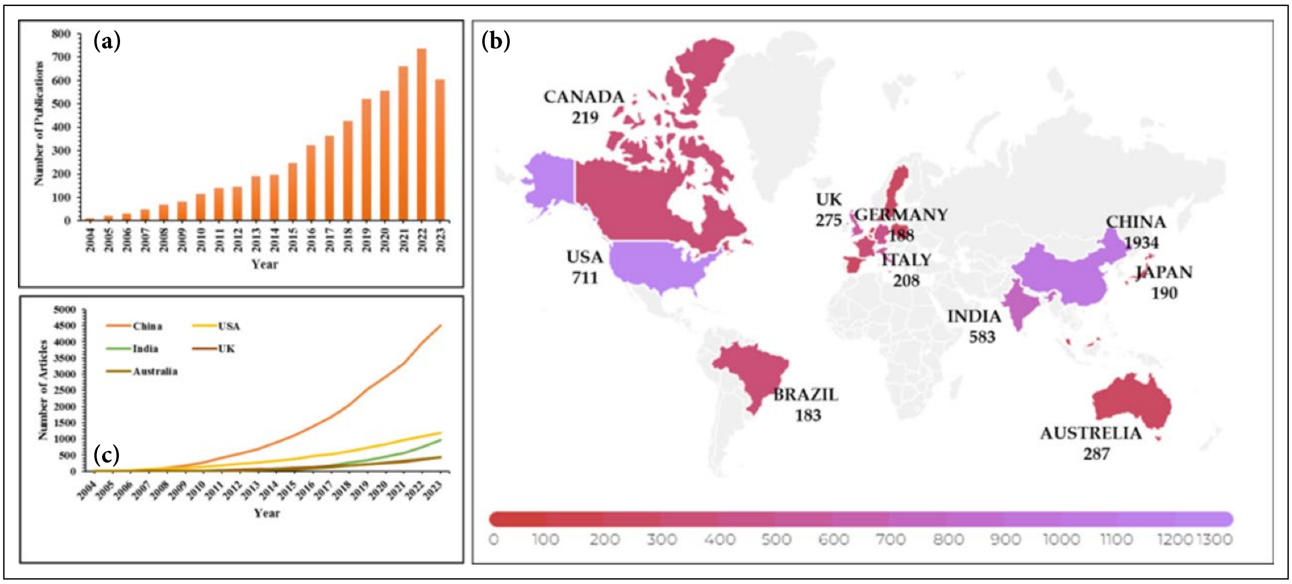

Figure 2. **(a)** Year-wise growth in the global electronic waste management research in the last twenty years (2003–2022), **(b)** Most productive countries doing research in e-waste management, **(c)** Top twenty keywords used in the articles on e-waste management.

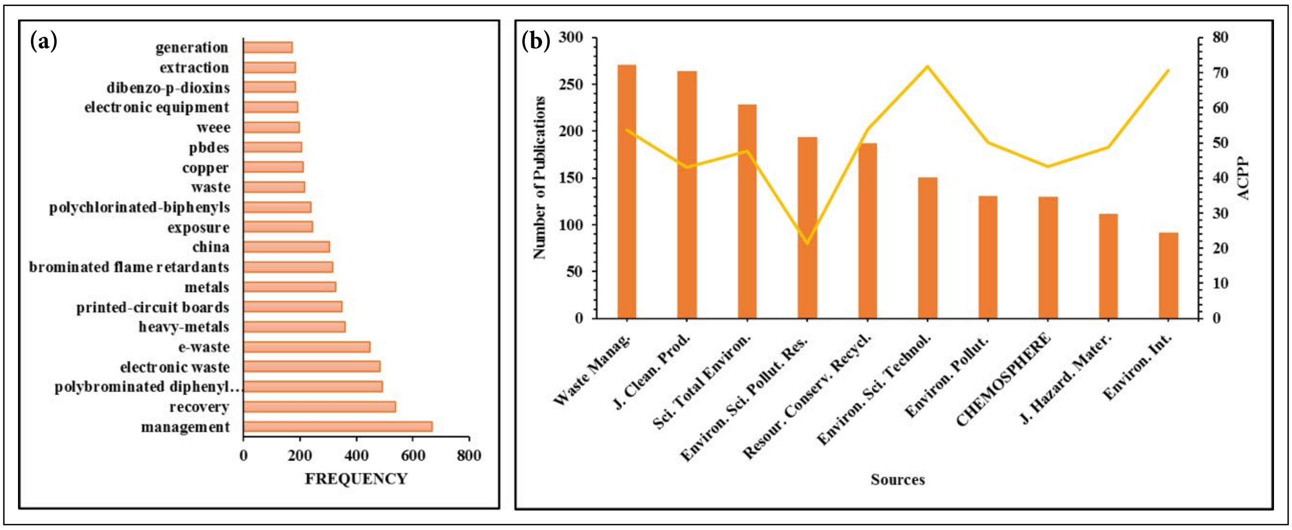

Figure 3. **(a)** Top twenty keywords used in the articles published on e-waste management, **(b)** Top tenjournals publishing articles on e-waste management along with average citations per publication.

The intensive investigation of the research articles published on e-waste management in the last two decades span is the motivation for discussing the environmental and health hazards, conventional processes (such as, landfill disposal, reuse, recycling, metal recovery from waste PCBs), and advanced processes [such as, lifespan extension (LE), life cycle assessment (LCA), materials flow analysis (MFA), multiple criterion analysis (MCA), extended producer responsibility (EPR) and extended consumer responsibility (ECR)] in a single review. Owing to the social responsibility, as well as, environmental benignity, the sustainable e-waste management favoring circular economy has also been highlighted.

PROBLEMS WITH E-WASTE

Electronic wastes contain many toxic chemical entities. The lack of proper disposal and management is threatening for health, as well as, environment. Scientific and research communities around the globe are actively engaged in research devoting in the management of electronic wastes to minimize the hazards associated with these toxic chemicals towards lives and the environment [20, 21]. The conventional practices of waste disposal, like, open dumping, landfill, incineration can causes soil, water, and air pollution [22]. Different electronic parts are associated with different hazardous chemicals and thus require complex procedures to manage these hazards and to get rid of the pollution associated with e-wastes.

Impact on Human

E-waste can affect human health in two different ways-

(1) Food chain issue: e-wastes contaminates food on open dumping through coming into the food chain and become a part of food eco-systems

Table 3. Hazardous chemicals, their sources and their impacts on human health [22–28]

Hazardous chemicals	Sources	Effects
Arsenic (As)	Microchips	Can cause several skin diseases along with lung cancer, liver and kidney diseases. Increases the rate of heart attack and significantly retard birth weight of child with associated neurological disorders.
Lead (Pb)	CRTs, TV, monitors, PCBs	Can severely damage nervous systems in children; Can affect blood circulation, reproductive as well as, nervous systems in adults.
Mercury (Hg)	LCDs, CRTs, PCBs, thermostats, sensors	Can damage brain and central nervous system badly; It can also damage kidney, liver, and immune systems. Inhibit fatal growth.
Cadmium (Cd)	Batteries, PCBs, CRT glass, toners, plastics, and infrared detectors	Highly toxic on human consumption. It can damage severely kidneys, bones and reproductive systems.
Antimony (Sb)	Semiconductors and PCBs	The exposure to antimony can produces skin problems like, redness on the skin, dermatitis etc. It can also cause headache, nausea, vomiting, insomnia, and abdominal pain.
Chromium (Cr-VI)	PCBs and metal housings as corrosion resistant	Highly toxic human carcinogens. It can affect reproductive systems and endocrines in human body.
Beryllium (Be)	Computer parts, electrical boxes, ceramic components	Can severely damage lungs, heart, liver, kidneys and central nervous systems.
Nickel (Ni)	Ni-Cd batteries, CRTs	Accelerates lungs, heart and neurological diseases.
Barium (Ba)	CRTs, fluorescent lamp	Can led to cardiac and respiratory failure, gastrointestinal dysfunction, and even paralysis.
Cobalt (Co)	Rechargeable lithium-ion batteries	Cobalt can yields asthma like allergy, such as, wheezing, cough. It can also led to heart, thyroid and kidney diseases.
Lithium (Li)	Batteries	Exposure to lithium can led to nausea, diarrhoea, dizziness, muscle weakness, and fatigue.
Polyvinyl chloride (PVC)	Wires and cables	Management of PVC through incineration produces chlorinated dioxins and furans which remain in atmosphere for longer period causing respiratory diseases on inhaling.
Zinc (Zn)	CRTs, batteries	Can cause Cu deficiency (anaemia and neurological disorders)
Brominated flame retardants	Boards and casing of electronic components	Can sustain in environment for longer period, neurotoxicity. Long exposure can affect learning and memory functions along with hyper and hypothyroidism.

(2) Direct exposure to worker: The conventional practice of waste management led to toxic chemicals inhaled by the worker during incineration. The direct exposure of these toxic chemicals led to several health damages.

Different hazardous chemicals originated from electronic wastes, their sources and their impact on human health has been summarized in Table 3. As can be seen, different electronic components contain significant amount of hazardous chemicals, which includes both heavy metals, toxic polymers and flame retardants. Heavy metal, such as, Pb and Hg can severely affect the central nervous system of human body. Lead is reported to adversely deteriorate the mental health of kids along with damage in the reproductive and renal systems [29]. Pregnant women are prime sufferers from mercury, affecting fatal growth. Figure 4 represents the health hazards associated with the toxic chemicals liberated from e-wastes on disposal. As has proved itself to be very lethal to mankind, causing lungs, kidney, and liver cancer along-with severe cardiac arrest. The detrimental effect of other elements like Sb, Cd, Cr(VI), Be, Ni, Co, Li etc. is also worthy to mention. Human gets exposed in a variety of pathways to the e-wastes. The informal sectors close to the e-waste disposal, as well as, recycling facility are the main victims for such kind of pollution. According to International Labour Organization, the kids of the family of these workers get contaminated easily with these lethal elements and chemicals, often designated as home exposure [30]. The unscientific disposal of e-wastes in dumping ground led to the contamination of soil from the hazardous metals present in it. The toxic chemicals thus come into the food chain, showing its lethal action to the human on exposure. A study by Tsinghua University, China suggests absorption of majority of toxic chemicals through nutritional path, during disassembling work [31].

Impact on Environment

The unplanned and unscientific disposal of e-wastes is harmful not only towards human being but also towards environment. Conventional practices of waste management, such as, incineration, open dumping, landfill may accelerates severe damage to the environment. Figure 5 depicts the adverse effect of the unscientific e-waste management practices towards the environment. As can be observed, air, water and soil may get polluted associated with the usual procedures of electronic waste management. The disposal of e-wastes through landfilling or open dumping

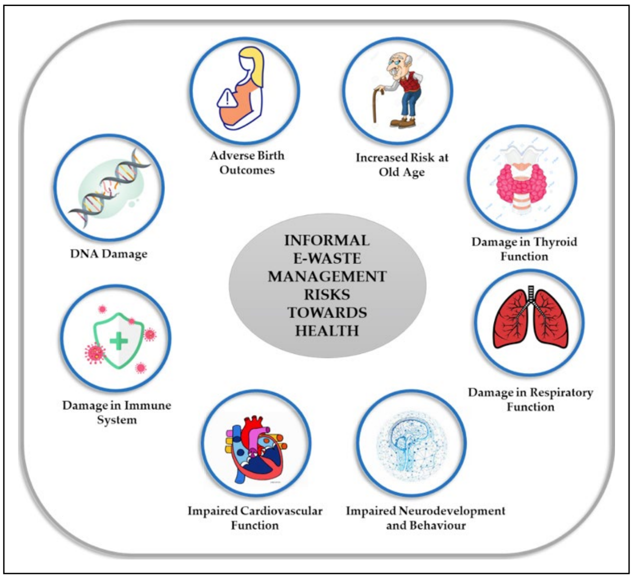

Figure 4. Impact of informal e-waste management towards human [32].

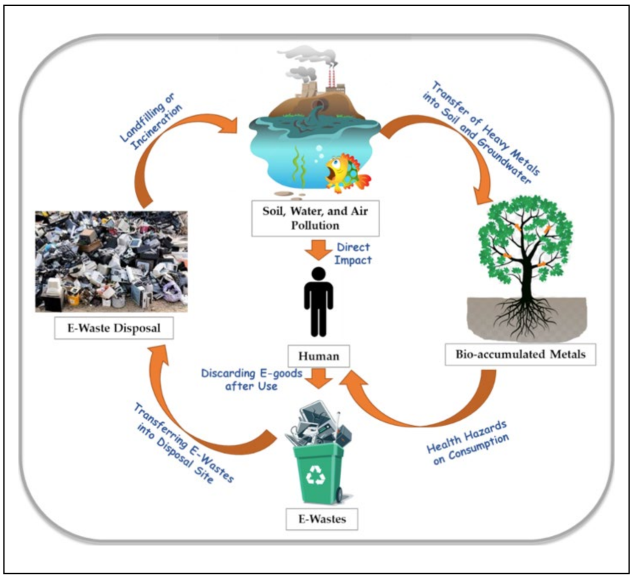

Figure 5. Impact of informal e-waste management towards environment [35].

may contaminate the soil by virtue of the presence of the heavy metals and other organic pollutants in the waste materials. Moreover, the leaching of these hazardous materials may lead to the contamination of ground water resulting water pollution. The presence of heavy metals, and organic matters in soil may affects plants, microorganisms, crops etc. The heavy metals may thus come into the ecosystems and displays its harmful effects towards the lives on earth. Additionally, the existence of the toxic chemicals in the soil changes the pH of the soil, destroys the micronutrients, affecting adversely the growth as well as its productivity. The ground water may become polluted in addition to soil pollution as consequence of open dumping or land filling of the electronic wastes. The water bodies as well as the animal kingdom may get suffered due to the presence of the toxic entities in the ground water. The quality of drinking water may get deteriorated associated with the presence of the heavy metals and other toxic pollutants and thus the existence of biodiversity become questionable [33]. The management of e-wastes in terms of incineration may degrade the quality of air by enhancing the amount of the harmful chemicals in terms of particulate matter in the air. Living beings may get damaged physically associated with the inhalation of the toxic chemicals during respiration.

The electronic waste management thus negatively impact environment and lives in the ecosystems. The human being, including adults, pregnant women, and children suffer badly from the e-waste pollution. Proper precautions need to be undertaken in managing the electronic wastes to maintain the sustainability of the ecosystems [34].

E-WASTE MANAGEMENT PROCESSES

The end usage of electronic wastes necessities the management of these accumulated wastes to minimize its harmful effects towards the environment and the lives on the earth. As the reuse, refurbish, or recycling strategies involve utilization of the e-wastes in other purposes, it is expected to evoke less harm towards the environment and the health. Some important e-waste management strategies has been discussed below.

Landfill Disposal

Landfilling is considered to be most common and easiest way of disposal of any solid wastes. Disposal of electronic wastes through landfilling has proved itself to be the most convenient way of e-waste disposal. The landfilling of e-wastes results in the release of polluting metals and other hazards naturally into the environment for years, leading to the severe damage to the ecosystem. The disposal of batteries through landfilling may led to the leaching of mineral acids and heavy metals, such as, nickel, lead, mercury, cadmium into the soil and also to the groundwater [36, 37]. The presence of these heavy metals into the soil, as well as, in the ground water leads to the contamination of rivers, ponds, and streams. Animals and individuals are found to be suffered from serious health issues associated with the toxicity of the metal ions and other pollutants [38]. Organic materials are also found to display their hazardous activities associated with their degradation into toxic fragments [39].

Thermal Treatment

Electronic wastes can also be disposed of through thermal processes like, incineration and pyrolysis. Incineration involves discarding electronic wastes through burning instead of landfilling them [40]. This process involves the reduction of the volume of the waste materials through burning and the energy recovered from the burning of combatable material can be utilized to carry out other processes. On the other hand, pyrolysis leads to the conversion of the waste materials into fumes, oils, and charcoal. The burning of PVC or plastic boards generates toxic gases consisting of polycyclic aromatics, dioxins, and polychlorinated dibenzofurans. Additionally, several gases of carbon, sulfur, and nitrogen along with the emission of heavy metal oxide occur. In spite of the simple and economically viable process, the thermal processes are generally avoided owing to their significant evil effects towards the environment [41, 42]. In addition, the incineration plants are reported to gather significant amount of cadmium and mercury [43, 44].

Reuse Process

The refurbishment process offers the reuse of the electronic wastes after minor repairing. The repairing of the electronic wastes not only favors its use for the second or third time but also helps to reduce the generation of electronic wastes. However, the process of refurbishment sometimes gets retarded owing to the least interest from the stakeholders.

Recycling Process

Recycling involves physical procedures to make the waste material competent in the same or some different application. The components of the waste materials are recovered by disassembling followed by disintegration. The recycling process has established itself as an efficient method for recovering valuable materials from wastes and utilizes them in some other purposes. As the process involves reutilization of the waste materials in some purposes, it is expected to inhibit pollution associated with the disposal of electronic wastes into the environment along with the restoration of the non-renewable virgin polymer. The recycling process thus found to save significant amount of energy [45]. The key goal of recycling is to minimize the contamination of the environment by the hazardous toxic chemicals from the electronic waste scrap and ensure the recovery of maximum material. For effective recycling, proper strategy needs to be adopted for the electronic waste material under consideration [46].

Recovering Metals from Waste Printed Circuit Boards (PCBs)

Printed circuit boards are inevitable part of any electronic product and thus with technological growth the amount of electronic wastes consisting of PCBs are also found to be increased. PCBs require special attention during management owing to their complex structures along with the presence of different kinds of materials [47]. PCBs are typically consists of three parts, viz., an insulating laminate, metallic conducting path, and different types of electronic components, including integrated circuits, registers, processor, transistors, capacitors etc. The insulating laminate is found to contain glass fiber reinforced plastics and some flame retardants. Several polymers, such as, polypropylene, epoxies, polyethylene and polyesters are generally utilized in the fabrication of PCBs [48]. The PCBs are thus required immense attention during their disposal. The unscientific and informal disposal of PCBs is not only a great threat towards the health and environment but also led to significant economic liability owing to the loss of valuable metals during treatment. Several methods have been developed by scientific communities around the globe to recover the valuable metals present in the PCBs and control the pollution associated with the disposal of these PCBs. The recovery process consists of three steps: pretreatment of the waste, their size reduction, and metallurgical treatment of the crushed wastes. The pretreatment step consists of disintegration of the board along with its compositional analysis [49]. After pretreatment the board is then shredded and screened according to the size [50, 51]. The third step consists of metallurgical techniques for recovering valuable materials as discussed below. Figure 6 summarizes different procedures for recovering valuable metals from waste PCBs.

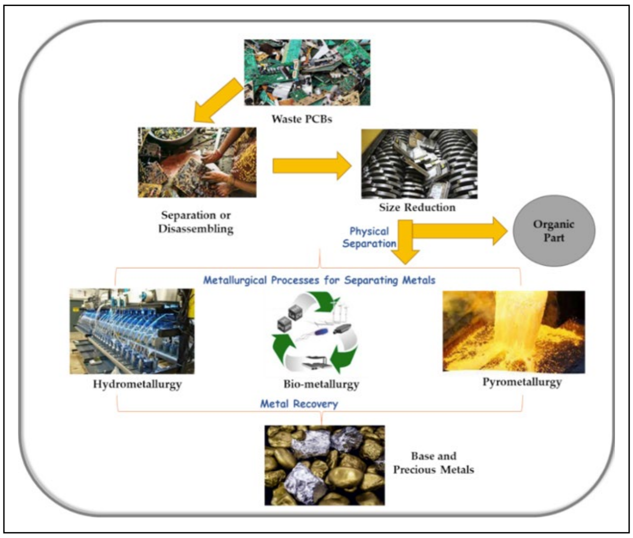

Figure 6. Procedures for metal recovery from waste PBCs [63].

Pyrometallurgical Processes

Pyrometallurgical processes offer several types of thermal treatments, which include smelting, sintering, drossing, and melting at elevated temperature [40]. These processes are used along with the thermo-physical separation of metal phase from the waste PCBs. For efficient and faster separation of metal from PCBs appreciably high amount of energy needs to be provided [52]. During industrial processes, the maximum energy can be utilized by several pre-treatment processes like, physical segregation, dismantling before smelting; a copper alloy consisting of precious metals typically generated [53, 54]. Pyrometallurgy is generally utilized in the separation of a metallic part from the non-metallic slag; the incineration of the organic component occurs. The other metal recovery processes, such as hydrometallurgy, biometallurgy are generally combined with pyrometallurgy to recover individual metals effectively [48].

Hydrometallurgical Process

Hydrometallurgical process is executed for recycling the metallic part present in the printed circuit boards economically. This process involves dissolution of the waste materials into the mixture of strong acids or bases, such as, sulphuric acid, hydrochloric acid, nitric acid, aqua regia, and alkalis [55]. The preferred metal can be extracted from the metal solutions by processes like electrorefining, adsorption, precipitation, solvent extraction and ion-exchange [56]. In developed countries, the recovery of metals from electronic waste materials was initiated in the late 1960s [57]. Precious metals, like silver and gold can be recovered in highly refined form employing this hydrometallurgical procedure [58]. The leaching solutions were found to be altered in different period of time. Cynaide leaching was widely employed for a longer period for extracting silver and gold in the form of dicyanoaurate or dicyanoargentate complexes [59, 60]. However, owing to the toxicity of cyanide, several non-cyanide leaching reagents, such as, thiosulphate, thiourea were proposed as the alternative leaching agents in the later period [61, 62].

Biometallurgical Process

Biometallurgy is actually the combination of two processes, viz., bioleaching and biosorption. Biosorption involves physico-chemical interaction between the microorganisms and the ions present in the solution. The microorganisms may be in the alive or dead condition. Various microorganisms, viz., algae [64–66], bacteria [67, 68], and fungi [69] are efficient in isolating heavy, as well as, precious metals from electronic wastes. Sheel and Pant [70] have recently reported a novel method involving leaching-sorption for recovering gold from e-waste utilizing ammonium thiosulphate and Lactobacillus acidophilus. Biosorption, as compared to the conventional method of metal isolation, provides several advantages, including, low operational charges, handling of less chemical sludge, and its high efficacy towards the process [71, 72]. Mack et al. [72] isolated gold (III) from leached wastes using Desulfovibrio desulfuricans biomass. The success of the bioleaching process is directly related to the efficacy of the microorganisms in the transformation of the solid compounds into soluble form. Several microbiological leaching processes have been executed in the last twenty years to mobilize metals from electronic wastes [73–75]. Acidophilus microorganisms, such as, Acidithiobacillus ferrooxidans, Acidithiobacillus thiooxidans, and Leptospirillum ferrooxidan has been reported as efficient microbe in the bioleaching process. Penicillium and Aspergillus niger are reported as efficient fungi in the isolation of metals from industrial wastes [76]. Another efficient method of bioleaching involves redoxolysis in the presence of acids and complexes [77, 78].

ADVANCED PROCESSES OF E-WASTE MANAGEMENT

The advanced formal processes of e-waste management involves different novel terminologies, such as, lifespan extension (LE), life cycle assessment (LCA), materials flow analysis (MFA), multiple criterion analysis (MCA), extended producer responsibility (EPR) and extended consumer responsibility (ECR). These systematic procedures have been adapted by developed countries to inhibit the pollution associated with e-wastes and uplift the environmental quality. The sustainable e-waste management starts with collection, separation and segregation of the waste materials followed by procedures for recovering precious metals. The parameters related to systematic e-waste management has been discussed below.

Lifespan Extension (LE)

Lifespan extension can be considered as a effective way for reducing e-wastes. Product's lifespan is defined as the period starting from its operational start to its discarding by the end owner [79]. This period consists of any kind of repair, refurbishment, and hibernation, when the product is not in use. As soon as the product is disposed off it comes into the environment as e-wastes and displays its aggravating effects towards the environment. To minimize its impact European Commission encouraged the extension of product's lifespan [80]. Bakker et al. [81] suggested an optimum lifespan of refrigerator 20 years and that of a laptop 7 years. These values are far greater than the average lifespan of 14 years and 4 years for refrigerator and laptop, respectively. Elevli found that the periodic maintainence and upgradation can effectively extend the lifespan of computer [82]. However, the technological advancement have limited the lifespan of e-products, such as, computers, laptops, smartphones, tablets, washing machines etc. The new technologies developed in the era of its operation have directed consumers towards replacing old gadgets by the newer one.

Life Cycle Assessment (LCA)

Significant research effort has been put towards LCA of electronic gadgets in relation to eco-friendly design, and environmental hazards. The environmental, as well as, economic impacts should be taken into consideration towards designing electronic device. LCA, for instance, offers systematic inhibition of environmentally pollution creating parameters, such as, carcinogens, ozone layer, climate change, soil character etc. The geographical distribution of LCA tool in the e-waste management suggests its initiation in Europe, followed by other continents like Asia, North America etc. [83]. It is worthy to mention that, Europe started its attention in the e-waste management two decades back, and thus has become technologically sound with time. Thus, the recycling and reuse of the e-waste materials is well administrated by the laws of European Parliament, restricting emission of hazardous substance into the environment. EU is considered as the pioneer in utilizing LCA tool in managing e-wastes. There has been extensive research conducted on LCA to assess the environmental consequences associated with the end-of-life (EoL) treatment of e-waste. For instance, the tack-back policy of e-wastes in Switzerland and its impact on environment was explored well by Hischier et al. [84] As observed, the take-back policy along with recycling appeared to be superior as compared to that of conventional incineration process owing to the sustainability of the environment and human health. The study by Barba-Gutiérrez et al. [85] revealed recycling of e-waste materials to be the most effective way for treating e-wastes considering the aggravating effect of the respiratory hazards towards the human health.

Material Flow Analysis (MFA)

The export of e-wastes from developed countries to the developing territories like India, China for reusing or recycling purpose were executed before the restrictions associated with the Basel Convention come into the force. The MFA technique is employed for examining the trajectory of materials, specifically e-waste, as it moves towards recycling facilities, disposal sites, and material stocks over a given period. This approach establishes connections between the origins of materials, the pathways they follow, and their ultimate destinations, encompassing both intermediate and final stages. MFA have proved itself to be very efficient tool within the realm of environment and waste management and thus this tool can be utilized in designing proper e-waste management scheme considering its economic, environmental, and social impact [86]. For instance, the flow of e-wastes in Asia was explored well by Shinkuma and Nguyen Thi Minh; the second-hand e-waste materials from Japan were reused in countries like Vietnam, Combodia etc. while the majority of e-wastes were informally recycled by China [87]. Aydin [88] utilized this MFA tool to optimize the capacity of solid waste management in Ankara, Türkiye. Streicher-Porte [89] employed MFA in conjunction with economic value assessment to conduct a comprehensive system analysis of the flow of Au and Cu derived from personal computer recycling in India. Their findings indicated that due to the significant concentrations of Au and Cu present in the recycled materials and the high value associated with these metals, recyclers were able to generate profits.

Multi Criteria Analysis (MCA)

According to Garfi et al. [90] MCA is defined as a strategic tool to resolve the complex issues considering qualitative, as well as, quantitative aspects of a problem. This tool has proved itself to be an efficient tool in the sustainable e-waste management to get rid of the environmental, as well as, health hazards associated with it. For instance, this MCA tool was utilized by Hula et al. [91] to optimize the management of waste coffee maker in terms of environmental sustainability and economic benefits.This modelling approach can also be applied in setting up methodology, as well as, selecting proper location for the establishment of new industries for recycling of e-wastes. For instance, in Spain, the MCA tool was utilized in selecting the best location for establishing e-waste recycling plant [92]. The selection process was based on the quantitative parameters involving warehouse location and economic aspects. The alternative processes of e-waste management were also designed computationally by Rousis et al. [93] Twelve different management strategies were compared and numbered according to their efficacy and suitability. The most effective way is to disassemble the complete e-waste part followed by processing for recycling of the eligible part; the remaining part can be discarded as landfilling. Although MCA is not a widely accepted tool in the e-waste management, it is generally utilized in addition to other tools to fulfil the social responsibility associated with the e-waste hazards [29, 94].

Extended Producer Responsibility (EPR)

The EPR approach is an environmental policy that assigns liability of the manufacturers for reclaiming products once they are no longer in use; it is operated on the basis of the polluter-pays norm [95]. This EPR policy is widely imposed in advanced nations, like European Union, Japan, and some parts of United States and Canada. This policy was initiated in 1991 by the EU and came into regulation in 2004 for taking back the e-wastes for treatment and recycling. The WEEE Directive (Directive 2002/96/EC) of the EU was formulated to establish regulations concerning electronic waste and its management. These regulations were developed with the principles of EPR in mind. The legislation sets forth the responsibility of producers in managing e-waste throughout its lifecycle, ensuring environmentally sound practices for EoL activities such as reuse, recycling, and recovery of electronic waste (EU, 2002). In the late 1990s, Japan introduced an environmental policy that focused on the responsibility of managing electronic waste (e-waste). This policy is regulated through two key laws: the Specified Home Appliances Recycling (SHAR) Law and the Electric Household Appliance Recycling Law. The SHAR Law was promulgated in 1998 and became effective in 2001. These laws establish regulations and guidelines for the recycling and proper disposal of electronic household appliances in Japan [96]. The SHAR law was implemented to facilitate the collection and proper disposal of electronic waste, specifically targeting large household appliances such as television sets, refrigerators, air conditioners, and washing machines. This law ensures that these items are taken back for recycling and appropriate treatment. Additionally, Japan has the Promotion of Effective Utilization of Resources (LPUR) Law, which addresses the management of personal computers and used batteries, aiming to promote their effective utilization and proper disposal to minimize environmental impact [97]. Additionally, this EPR policy also escalated Design for Environment (DfE) during fabrication of new electronic product. The electronic manufacturers have successfully developed printed circuit boards devoid of lead bromine to get rid of the environmental hazards associated with them [14].

Extended Consumer Responsibility (ECR)

The success in effective e-waste management lies in the perception of consumers towards e-wastes in addition to the government and producer based initiatives [98, 99]. ECR in e-waste management refers to the active participation of consumers in the systematic e-waste management and thus escalating recycling, minimizing the environmental and health hazards associated with it [100]. The detrimental effects of e-wastes appear to be very much unrevealed to the consumers [101]. In addition, people sometimes do not agree to consider e-wastes as hazardous, as well as, toxic [102]. This is a very common scenario in both the developing and developed countries. In USA, for instance, the unwilling of consumers restrict-

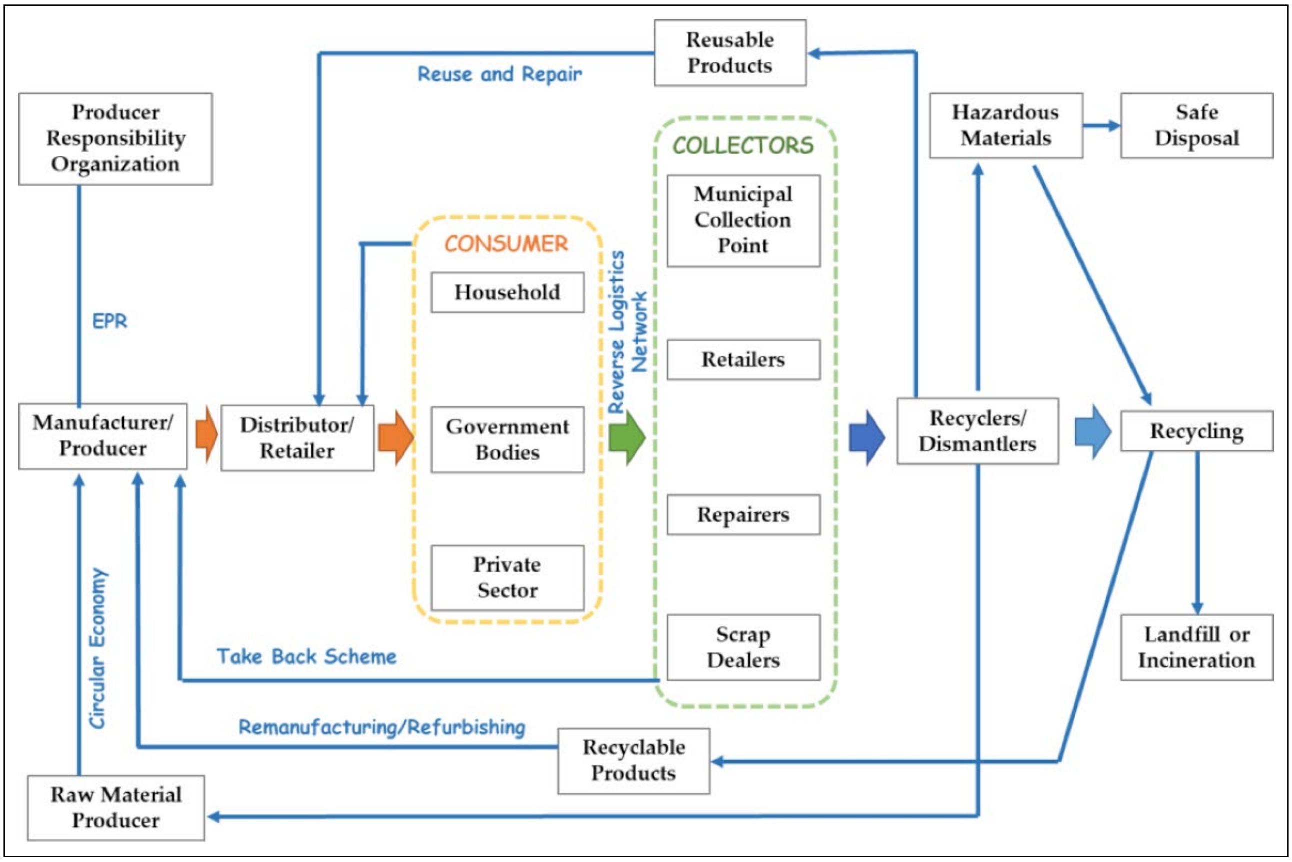

Figure 7. A sustainable approach for e-waste management, adapted from [106, 107].

ed themselves in transferring the e-waste materials to the recycling facilities associated with the lack of consciousness, as well as, inadequate information available with it [103]. Siringo et al. [104] suggested the environmentally sustainable practices in individuals can be achieved through the change in behaviour through motivation. The morality, environmental concern and social responsibility are expected to direct individual to promote sustainable practices like recycling. Governments and non-governmental organizations can play a vital role in educating consumers through awareness campaigns and endorsing legislation that promotes EPR.

Utilization of Each Distinct Tool in the Systematic E-Waste Management

The success in the proper e-waste management lies in eco-friendly design, proper scientific collection of e-wastes, recovering/separating precious/hazardous metals by safe procedures, recycling the eligible part, safe disposal of the remaining part, and raising awareness in the producers and users. Most of the developed countries and also few developing countries are following these strategies for managing their accumulated e-wastes. Some developing countries are still struggling over to establish proper network for e-waste management. Proper training of the users, as well as, the other stakeholders should be executed to make the e-waste management process eco-friendly. It is noteworthy that, the strategies, such as, LCA, MFA, MCA, and EPR have proved itself to be competent in resolving the detrimental issues associated with e-waste management. Every tool utilized in e-waste management possesses distinct characteristics and features that differentiate them from one another. For instance, LCA offers several benefits in supporting e-waste management. LCA enables the estimation of material consumption effects, thereby influencing the development of eco-designed products. Additionally, LCA facilitates the evaluation of both environmental and economic aspects associated with the EoL disposal of electronic devices. On the contrary, MFA is utilized to explore the flow of e-waste materials, estimating waste generation, and its proper recycling or disposal. This strategy is widely used in developing territories like, China, India, where larger recycling plants were established to deal with the e-wastes exported from developed countries. MCA is powerful modelling approach for developing useful strategies, and selecting proper location of establishing recycling plants, owing to environmental and economic benefits. Although, MCA has proved itself as powerful tool for managing hazardous solid wastes, it is widely used in managing e-wastes. EPR is a powerful tool focusing on the responsibility of the producer to take back the e-wastes from the user after being dysfunctional. This EPR strategy is currently being employed in developed, as well as, developing territories like, Japan, Germany, India, Thailand, Netherlands, UK, and USA. However, different countries have modified their EPR policies as per their convenience to make the process suitable for them.

SUSTAINABLE E-WASTE MANAGEMENT

The sustainable management of electronic wastes necessities proper planning and strategies from policymakers around the globe [105]. The strategies should include proper utilization of existing technologies, easy and economically viable procedure, minimization of environmental pollution, and consumer awareness. The advanced technologies for recovering metals from e-waste, such as, pyrometallurgy, hydrometallurgy, bio-metallurgy should be included in the sustainable waste management procedures. The key challenge in the electronic waste management lies in the collection of different electronic waste materials from different sources and their proper segregation. One interesting study by Forti et al. [19] suggests, out of the total electronic wastes generated globally, only 17.4% were collected while the rest 82.6% were remained as abandoned. This fact suggests significant lacunae in the policies of e-waste management. Thus, the success in the sustainable e-waste management lies in the sincerity and responsibility of each and every stakeholder associated with it. Government should take initiative to make proper guidelines for consumers, manufactures, traders, and recyclers. Proper regulatory body should also be there to supervise each step of management and ensure proper recycling of e-waste materials to maintain environmental serenity. Local bodies can play an important role in the collection and segregation of e-wastes. Transportation of electronic wastes has always remained a major challenge associated with the indefinite amount of e-wastes from different cities. To get rid of the associated hazards, the electronic wastes from developed countries are transferred to developing countries, where the legislation related to electronic wastes are flexible and thus the electronic wastes are informally treated leading to severe damage to the eco-system. Sustainable transportation of electronic wastes can only be reached by developing proper channel of collection and transferring the segregated wastes to the respective recycling stations. All the stakeholders, viz. manufacturers, consumers and recyclers play vital role in the smooth operation of the e-waste management. Figure 7 represents a schematic approach for sustainable e-waste management.

CIRCULAR ECONOMY (CE) AND SUSTAINABLE DEVELOPMENT GOALS (SDGS)

The informal and unlawful management processes of e-waste management are creating significant damages in the human health and environment. The deterioration in the economy is also evident associated with the conventional practices of e-waste management. The traditional methods like, landfilling and thermal treatment is very much unlikely in terms of economic aspects as it led to severe damage in the economy associated with significant loss in terms of transportation and labour. However, the proper sustainable strategies may lead to inhibit environmental hazards along with escalating circular economy (CE). In addition, it creates several job opportunities along with suppression of health and ecological hazards in the developing countries [108]. Numerous developing nations have well-established and dynamic repair and refurbishment industries that could benefit from additional assistance and support through international development initiatives to maximize their capabilities [109]. International development programs have the potential to provide further support to developing countries in maximizing the growth and professionalization of their existing vibrant repair and refurbishment sectors.

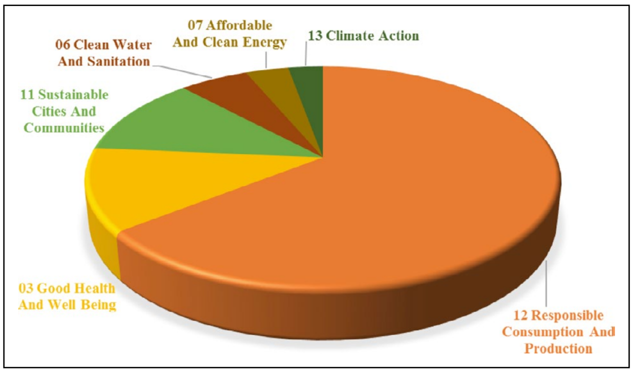

Figure 8. Sustainable development goals, expected to be achieved by the sustainable e-waste management.

The sustainable strategies of e-waste management may also help to attain nine sustainable development goals (SDGs) out of the seventeen SDGs as targeted by UN for 2030 (Fig. 8). The SDG 12, i.e. "Responsible Consumption and Production" appears to be the most achieved SDG, owing to the importance of awareness and behavioural setup of consumer, as well as, EPR policies in dealing e-wastes. The well-planned management strategies for sustainable development of the environment would favour "Good Health and Well-Being" as specified by SDG 3. In addition, the systematic, sustainable e-waste management practices are expected to favour "Sustainable Cities and Communities" i.e. SDG 11. The systematic e-waste management can also evoke "Clean Waste and Sanitation" as specified in SDG 6. The systematic e-waste management policies can again lead to "Affordable and Clean Energy" and "Climate Change" as targeted in SDG 7 and SDG 13, respectively. The unlawful disposal of the components of electric cars, as well as, silicon wafers from solar panels can be a secondary cause for climate change. The sustainable strategies of e-waste management can thus favours in restricting any change in climate associated with e-wastes.

CONCLUSION

The modern civilization, as well as, technological advancements is growing the amount of e-wastes generated globally. The statistical data suggests an e-waste generation of 59.4 Mt in 2022 and is expected to be reached 74.7 Mt in 2030. The European continent is found to recycle the highest amount (42.5%) of e-wastes, whereas, USA being a developed territory found to recycle <10% of its e-wastes generated. With rapid population growth, as well as, technological advancement, the generation of e-wastes is increasing day by day and has become a fact of emergent concern for scientific and research communities worldwide. Though the most developed territories generate the highest amount of e-wastes, little efforts has been put towards managing them. European countries, including UK, Germany, and France are managing significant amount of e-wastes responsibly. The bibliometric parameters associated with the e-waste management research suggest growing research interest of the worldwide research community in managing e-wastes. China found to contribute the highest number of articles in the era of e-waste management followed by USA and India. In addition, significant research focus has been put in the detrimental effects of e-wastes, recovery of heavy and precious metals from e-wastes, processes and policies associated with systematic e-waste management. The informal and unscientific management of e-wastes led to severe health and environmental hazards. The traditional waste management methods, such as, landfilling, and incineration expels significant amount of heavy and toxic chemicals to the environment, leading to severe air, water, and soil pollution. However, proper management strategies for e-wastes not only inhibit the associated harmful effect towards the lives on earth, but also favour circular economy. Strategies like, LCA, MFA, MCA, EPR displayed good potentiality to deal with the e-wastes after EoL. The sustainability of the strategies for managing e-wastes lie in the responsibility of all stakeholders associated with it. Additionally, the sustainable e-waste management is expected to fulfil several SDGs as targeted by UN for 2030.

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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.

USE OF AI FOR WRITING ASSISTANCE

Not declared.

ETHICS

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

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Review Article

Rising tide of ocean acidification

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ABSTRACT

This comprehensive review explores the escalating environmental crisis of ocean acidification, primarily driven by anthropogenic carbon dioxide molecule (CO_2) emissions. In this study, we employed a systematic methodology to collect and analyze literature relevant to ocean acidification. Our research involved an exhaustive search of databases such as PubMed, Web of Science, Google Scholar, and Mendeley to gather pertinent studies published up until 2024. In addition, we consulted secondary sources, including expert panel reports, to enhance the depth of our analysis. Socio-economic ramifications are profound, particularly for fisheries, tourism, and coastal communities that rely heavily on marine resources. This research underscores the potential for substantial exacerbates in these sectors, emphasizing the need for targeted policies and management strategies to mitigate the adverse effects of ocean acidification. By addressing these critical areas, the study informs stakeholders and supports the development of adaptive measures that can sustain local economies and preserve biodiversity in affected regions. The economic consequences could be substantial, exacerbating global social and economic disparities. Speculative considerations highlight the potential for significant global impacts and the urgent need for proactive, coordinated action. This review emphasizes the importance of continued research and monitoring to develop effective mitigation and adaptation strategies, underscoring the critical role of global cooperation and innovation in environmental management. This review aims to serve as a call to action, highlighting the urgency to preserve marine ecosystems and their services to humanity in the face of this growing environmental challenge.

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INTRODUCTION

Ocean acidification, one of the world's most important environmental problems, refers to the ongoing decrease in the pH of the Earth's oceans, primarily caused by the uptake of carbon dioxide molecules (CO_2) from the atmosphere [1]. When carbon dioxide molecules (CO_2) dissolves in seawater, it reacts to form carbonic acid (H_2CO_3), which lowers the ocean's pH, altering its essential chemical balance (Fig. 1) [2]. The absorption of human-generated CO_2 by the oceans leads to an increase in hydrogen ion (H^+) and bicarbonate ion (HCO_3^-) concentrations while simultaneously reducing carbonate ion (CO_3^{2-}) levels. This decline in carbonate ions results in the shallowing of carbonate saturation horizons, which can adversely affect the formation and maintenance of shells and skeletons in various marine calcifies such as foraminifera, corals, echinoderms, mollusks, and bryozoans. These changes in ocean chemistry directly result from increased atmospheric carbon dioxide molecules (CO_2) and represent a significant shift in the marine environment with potential impacts on marine biodiversity and ecosystem health [2, 3].

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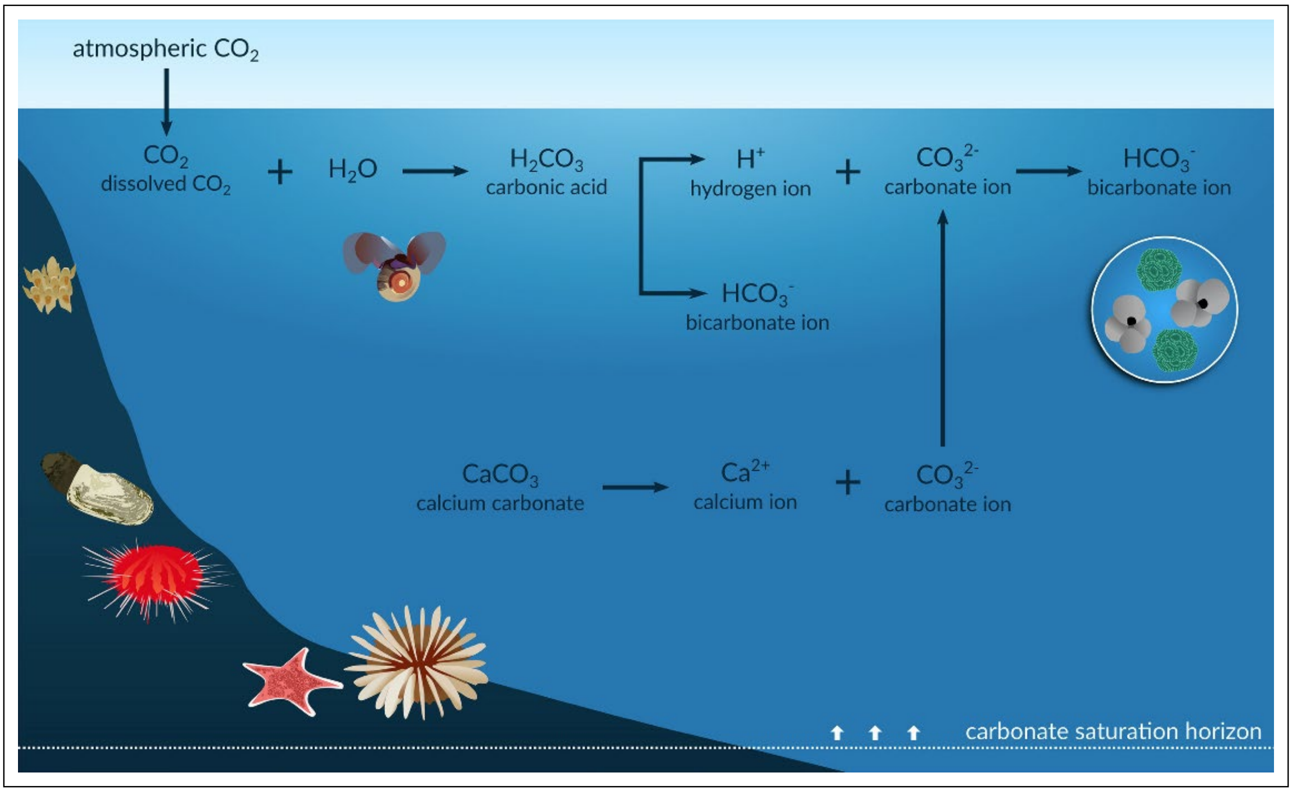

Figure 1. The process of ocean acidification [2].

In this study, we employed a systematic methodology to collect and analyze the literature relevant to the topic of ocean acidification. The research involved an exhaustive search of databases such as PubMed, Web of Science, Google Scholar, and Mendeley databases, which was conducted to gather pertinent studies published up to 2024. Additional secondary sources, including panel reports, were also consulted to enhance the depth of the analysis. The search utilized a combination of keywords related to "ocean acidification," "climate change," "algae," "ecology," and "Marine ecosystems." We established specific inclusion and exclusion criteria for literature selection: articles needed to be published in English between 1990 and 2024 and specifically address ocean acidification and environmental impact. The analysis aimed to identify patterns, trends, and gaps in the current research landscape. This helped me understand the effectiveness of different methodologies and the overall scope of research on the specified topic. Secondary sources, including panels on climate change, were primarily used to provide contextual background and support findings from the primary literature. This approach not only enriches the understanding of the subject matter but also underpins future research directions in this area.

This process has accelerated since the Industrial Revolution, with the Intergovernmental Panel on Climate Change (IPCC) reporting a 26% increase in ocean acidity since pre-industrial times [4]. The significance of ocean acidification cannot be overstated, given its profound impact on marine ecosystems. It mainly affects calcifying organisms such as corals, mollusks, and some

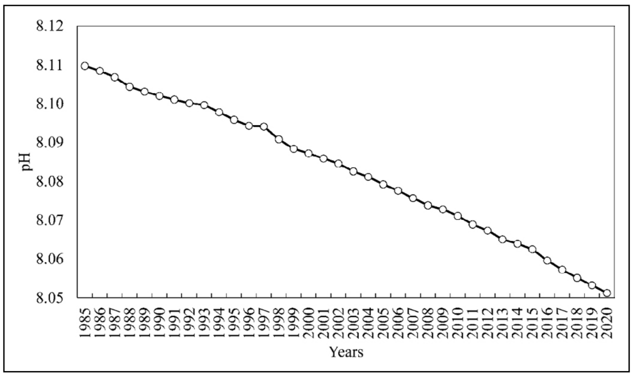

Figure 2. pH level of the oceans between 1985–2020.

plankton species, compromising their ability to build shells and skeletons, which are crucial for their survival and, by extension, the health of the entire marine food web [5]. The current rate of acidification presents an unprecedented challenge; studies suggest that the current rate is over ten times faster than any acidification in the last 55 million years; Figure 2 shows the pH level of the oceans between 1985–2020 [6]. This literature review aims to consolidate current knowledge on ocean acidification, identify research gaps, and inform effective policy and management strategies. By synthesizing a wide array of interdisciplinary studies, the review highlights areas needing further investigation and guides future research priorities. Additionally, it seeks to educate stakeholders and the public, enhancing awareness and fostering collaborative efforts toward mitigating the impacts of ocean acidification.

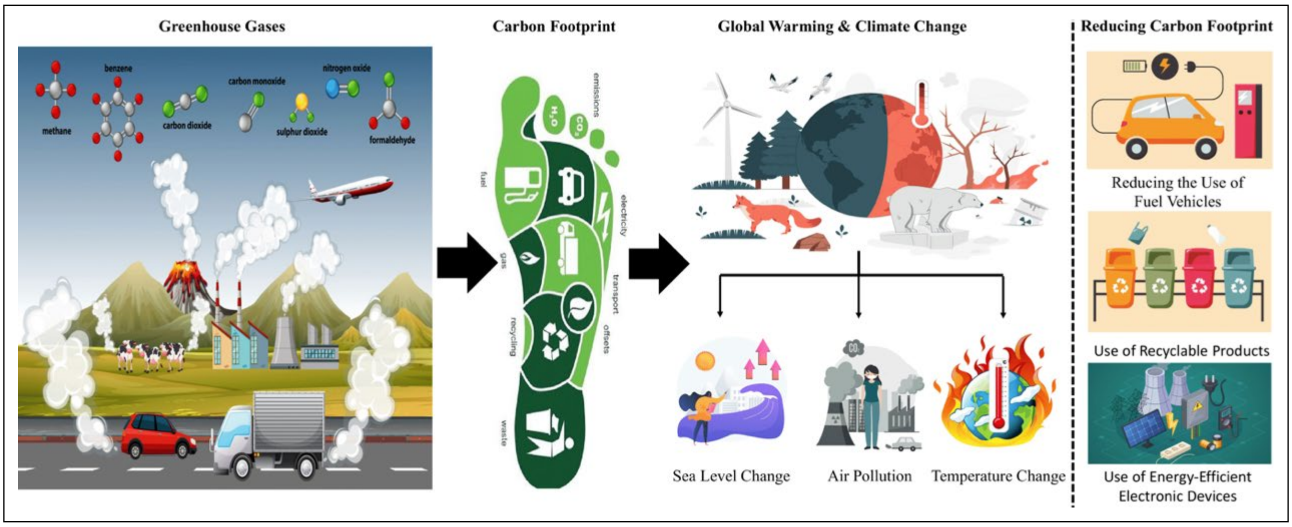

Figure 3. Carbon footprint context path [11].

FUNDAMENTAL CAUSES OF OCEAN ACIDIFICATION

Carbon Dioxide Emissions and Atmospheric Changes

The primary driver of ocean acidification is the increased concentration of CO_2 in the Earth's atmosphere [7]. According to the National Oceanic and Atmospheric Administration, atmospheric CO_2 levels have risen from approximately 280 parts per million (ppm) in the pre-industrial era to over 410 ppm today, primarily due to human activities such as fossil fuel combustion and deforestation [8–10]. The increase in CO_2 emissions, along with the rising carbon footprint values (Fig. 3) [11], leads to various issues, including climate change-induced human migrations [12–14]. Oceans absorb CO_2 produced by these activities, leading to significant changes in their chemical composition [15]. The dissolved CO_2 reacts with seawater to form carbonic acid, which dissociates into bicarbonate and hydrogen ions, causing a decrease in pH [16, 17].

Industrial and Agricultural Impacts

Beyond fossil fuel combustion, other industrial and agricultural practices and urbanization stress contribute significantly to ocean acidification [18–20]. Industries such as cement manufacturing release substantial CO_2, further exacerbating this issue [21]. Additionally, nutrient run-off from agricultural fields, particularly those rich in nitrogen and phosphorus, leads to eutrophication [22]. This process reduces oxygen levels in water bodies and contributes to acidification by producing nitrous oxide, another potent greenhouse gas [23]. Practices like deforestation and land use changes also play a role, as they decrease the Earth's capacity to absorb CO_2, leading to higher concentrations of this gas in the atmosphere [24]. Transitioning to functional foods with lower environmental impacts can reduce carbon emissions and serve as a measure against ocean acidification [25]. The intersection of these factors - increased CO_2 emissions, industrial practices, and agricultural activities - culminates in the progressive acidification of our oceans [26].

BIOLOGICAL AND ECOLOGICAL EFFECTS

Impact on Marine Life

Ocean acidification, primarily driven by increased atmospheric CO_2, critically impacts marine organisms, especially those that form calcium carbonate structures [27]. Research shows a direct correlation between acidification and the reduced ability of species like mollusks and certain plankton to maintain their calcium carbonate shells [5]. This weakening leads to higher mortality rates and reproductive challenges [28]. Additionally, studies have demonstrated that acidification can disrupt neural processing in fish, altering their behavior and diminishing their ability to detect predators [29]. Some of them are indicated in Table 1, affecting crucial ecological relationships.

Effects on Reef Ecosystems

Coral reefs, the biodiversity hotspots of the oceans, are particularly susceptible to acidification [32]. The process inhibits the availability of carbonate ions, essential for coral calcification [33]. According to a study by [33], a decrease in ocean pH by 0.1 units, which has occurred since the Industrial Revolution, can lead to a 20-30% reduction in coral calcification rates. This weakening of coral structures and other stressors like thermal stress significantly decline reef health and the biodiversity they support [34].

Long-Term Effects on Biodiversity and Ecosystem Health

The long-term implications of ocean acidification on marine biodiversity and ecosystem health are profound [35]. As individual species face survival challenges, the ripple effects can shift community composition and ecosystem function [36]. It was highlighted that acidification not only affected overfishing and habitat destruction but also posed a significant threat to the stability and productivity of marine ecosystems [37]. The loss of biodiversity and ecosystem services, such as fisheries and carbon sequestration, may have far-reaching consequences for global environmental stability and human well-being.

Table 1. Concise summary of critical studies on the impact of ocean acidification on marine species

Species affected	Type of impact	Key findings	References
Corals, oysters	Reduced calcification, shell thinning	Increased ocean acidity leads to the bonding of hydrogen ions with carbonate ions, making it difficult for these organisms to build and maintain calcium carbonate shells.	[1]
General marine species	Altered production of calcium carbonate	Around 30% of all CO_2 emissions are absorbed by the ocean, altering calcium carbonate production and affecting various marine species.	[27, 30]
Marine biodiversity (general)	Various impacts, including reduced calcification and skeletal structure	A comprehensive review of over 300 scientific literature showing alarming potential ecological scenarios and effects on marine biodiversity.	[31]
Marine calcifiers in the Southern Ocean	Variable impacts due to regional differences	Highlights how regional variations in ocean acidification affect different species, explicitly referring to the Southern Ocean and its marine calcifiers.	[2]

SOCIOECONOMIC IMPACTS

Effects on Fisheries and Marine Resources

Ocean acidification poses significant risks to global fisheries, a primary source of protein for billions worldwide [38]. A study by [39] indicates that mollusks, a key component of global fishing, are particularly vulnerable to acidification. The decline in mollusk populations due to their reduced calcification ability can lead to substantial economic losses [39]. For instance, the shellfish industry in the United States alone, valued at one billion dollars annually, faces significant risks [40]. Additionally, changes in plankton communities, the base of the marine food web, could alter fish populations, impacting fisheries and the dependent economies [41].

Impact on Coastal Communities and the Global Economy

Coastal communities are especially vulnerable to the effects of ocean acidification [42]. These communities rely heavily on marine resources for economic and food security [43]. A decline in marine biodiversity and fisheries can lead to loss of income, increased food insecurity, and reduced economic growth in these areas [44]. Furthermore, as coral reefs degrade, their protection against storm surges and erosion diminishes, threatening coastal infrastructure and homes [45]. Regarding tourism, fisheries, and coastal defense, the economic value of coral reefs is estimated to be tens of billions of dollars annually [46]. Globally, the financial loss due to reduced biodiversity and ecosystem services because of ocean acidification could be substantial, affecting industries from tourism to seafood and impacting global economic systems.

CURRENT RESEARCH AND FINDINGS

Scientific Studies and Experimental Results

Recent advancements in oceanography and climate science have shed new light on the multifaceted impacts of ocean acidification. Experimental studies are central to this research, providing critical insights into marine organisms' physiological and ecological responses to acidification. For example, [47] investigated volcanic CO_2 vents as natural laboratories to understand long-term ecosystem responses to acidification. They observed substantial shifts in marine communities where the water was more acidic, indicating potential future changes under continuing acidification.

In addition to organism-level studies, researchers are increasingly focusing on the ecosystem-level effects of acidification. The European Project on Ocean Acidification has conducted extensive research, revealing how acidification can alter nutrient cycles, food webs, and overall marine productivity [1]. These findings are crucial for predicting the broader ecological consequences of ongoing ocean pH changes [1].

Global and Regional Case Studies

Case studies from various parts of the world highlight the regional differences in the impacts of ocean acidification. Researchers have observed substantial acidification impacts on pteropods–tiny, shelled organisms vital to the marine food web in regions like the California Current System [48, 49]. A study [50] showed that these organisms are experiencing severe shell dissolution, which could have far-reaching effects on the marine ecosystem and fisheries.

Ocean acidification poses a unique threat in the Mediterranean Sea, a hotspot of biodiversity and endemism [51]. These changes have significant implications for the overall health of the Mediterranean marine ecosystem and the economies that depend on it [52]. Furthermore, acidification is affecting the Antarctic food web in the Southern Ocean [53]. Studies like those by [54] demonstrate that acidification can disrupt the availability of carbonate ions necessary for the growth of phytoplankton, the base of the Antarctic food chain. This disruption has potential cascading effects on the ecosystem, from krill to higher trophic levels like fish, seabirds, and marine mammals [54, 55].

MITIGATION AND MANAGEMENT STRATEGIES

Reduction and Adaptation Strategies

As the IPCC emphasizes, effective ocean acidification mitigation primarily hinges on reducing atmospheric CO_2 levels [56]. Strategies for CO_2 reduction include transitioning

Table 2. Ocean acidification mitigation strategies

Strategy	Description	Effectiveness	Challenges	References
Coastal blue carbon	Conservation and restoration of coastal wetlands like mangroves and seagrasses to sequester and store carbon.	Effective locally for buffering ocean acidification effects.	Limited global impact and reliance on habitat availability.	[76, 77]
Alkalinity enhancement	Increases the ocean's CO_2 storage capacity by changing seawater chemistry to absorb more CO_2 from the atmosphere.	Potentially valuable for mitigating acidification, albeit slowly.	There are many unknowns around the technique and its long-term impacts.	[76, 78]
Kelp farming & afforestation	It uses fast-growing kelp or other algae to capture CO_2, potentially mitigating acidification.	It may have local or seasonal mitigating effects.	Risk of displacing existing phytoplankton productivity, other negative impacts.	[76, 79]
Forecasting and management	Utilizes models and predictions to inform management strategies to protect marine resources and communities.	It helps in preparing communities and industries for future changes.	Dependent on the accuracy and reliability of models and predictions.	[76]
Technology development	Developing tools to monitor and mitigate changing ocean chemistry.	Supports localized mitigation efforts.	Requires technological advancement and widespread deployment.	[76]

to renewable energy sources, enhancing energy efficiency, and implementing carbon capture and storage technologies [11]. For example, wind and solar energy development has demonstrated significant potential in reducing fossil fuel reliance, as evidenced by the global growth of renewable energy sectors [57].

Adaptation strategies are also critical, especially for vulnerable marine ecosystems and communities dependent on them [45]. Aquaculture practices, for instance, can be adapted to be more resilient to changing ocean conditions [58]. Various biological and limnological monitoring applications can be applied to conservation strategies [59, 60]. Human impact also changes lake ecosystems [61, 62]. Research on the Pacific oyster industry in the United States [63] has highlighted the success of monitoring and buffering seawater pH as an adaptation measure. Just as some algae species have biotechnological properties for the treatment of harmful dyes, terraforming mars, functional foods, green building, biofuel, [64–69], and certain types of algae can also help in reducing ocean acidification [70].

Policy Recommendations and International Collaborations

Policy frameworks play a crucial role in addressing ocean acidification [71]. National policies, such as implementing rigorous emission reduction targets and promoting sustainable marine practices, are essential [72]. Internationally, the Paris Agreement under the United Nations Framework Convention on Climate Change sets a global framework for reducing emissions, but further action is needed to target ocean acidification specifically [73]. Some Ocean Acidification Mitigation Strategies are given in Table 2. International collaborations are vital for research, monitoring, and sharing best practices. Initiatives like the Global Ocean Acidification Observing Network provide platforms for international scientific cooperation, enhancing our understanding and capacity to respond to acidification [74]. Furthermore, integrating ocean acidification into global conservation and management strategies, such as those under the Convention on Biological Diversity, is imperative for a coordinated global response [75].

CONCLUSION

This comprehensive review of ocean acidification has revealed a critical environmental challenge characterized by the rapid increase in ocean acidification driven by CO_2 emissions from human activities. This phenomenon significantly impacts marine life, ecosystems, and socio-economic structures, with variations in effects observed regionally, suggesting that certain areas like the Arctic are experiencing changes faster than others. The impact on marine biodiversity and ecosystems extends beyond immediate effects on calcifying organisms such as mollusks and corals. The potential for cascading effects through the marine food web raises concerns about the collapse of specific ecosystems, leading to significant biodiversity loss. These ecological changes pose profound economic impacts, particularly on industries like fisheries and tourism and on coastal communities dependent on marine resources. The economic consequences could be severe, with global costs potentially reaching billions and exacerbating existing social and economic disparities. Emerging research and forecasting tools enhance our understanding of ocean acidification and aid in planning and response strategies. Innovative research is required to understand and forecast the long-term effects of acidification, with the development of new models and monitoring tools playing a crucial role.

Speculatively, biotechnological advancements may offer solutions to enhance the resilience of vulnerable species and ecosystems. To address these challenges, a multi-faceted approach is necessary. Reducing CO_2 emissions through renewable energy and carbon capture technologies is crucial. Equally important are adaptation strategies for marine ecosystems and human communities, strengthened policy frameworks, and international collaboration. Future international agreements might include specific targets and techniques for combating ocean acidification. The speculative possibility of innovative solutions highlights the potential for significant global impacts, emphasizing the critical need for proactive and coordinated action. In conclusion, the insights gathered from this study underscore the urgency of international cooperation and innovation in environmental management. Immediate and concerted efforts are needed to mitigate the impacts of ocean acidification and preserve marine ecosystems and their services to humanity. Though uncertain, speculative future scenarios reinforce the potential for innovative solutions and significant global impacts, emphasizing the critical need for proactive and coordinated action.

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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.

USE OF AI FOR WRITING ASSISTANCE

Not declared.

ETHICS

No need to ethical approval for this study.

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Review Article

Bioplastic an alternative to plastic in modern world: A systemized review

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ABSTRACT

Currently, plastic pollution is one of the biggest environmental concerns, and sustainable alternatives to traditional plastics are being explored. Using bioplastics, which are made from renewable resources and biodegradable, can reduce plastic pollution and promote environmental sustainability. This review article examines the role of bioplastics in today's society as alternative plastics. A variety of biodegradable polymers, including PLA, PHA, PBS, SB, CB and PUH, have been tested. Plastics made from bioplastics can be used in a wide range of industries, including packaging, biomedical devices, agriculture, and 3D printing. Despite tremendous advances, difficulties such as scalability, cost competitiveness, and end-of-life management remain, requiring additional research and innovation. For the development and implementation of bioplastic alternatives on a global scale, collaboration between academia, business, and governments is essential. Using bioplastics can reduce plastic pollution, greenhouse gas emissions, and promote a more sustainable future. In order to address the challenges of plastic pollution in the 21st century, it is important to switch to biodegradable and ecologically friendly materials.

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INTRODUCTION

One of the biggest problem of our's era is pollution and responsible for millions of death every year. Addition of any harmful material that reduce the environment's natural quality, causing adverse effects on ecosystem, or provide a health risk are considered as pollution [1]. Pollution comes from diverse sources, both natural like volcano eruption [2], forest fires [3], biogenic emission [4], dust storm [5], methane emission [6] and human activities e.g., industrial activities [7], transportation [8], agricultural practices [9], waste management [10], domestic use [11]. Pollution caused from these sources vary region to region but according to reported literature natural sources contribute 30% of global fine particular matter (PM 2.5) while rest 70% caused by human activities [12]. Similarly, 40% of global methane emission caused by natural sources and human activities contribute rest 60% [13]. Depending on the nature of pollutants, pollution is mainly classified as:

Air Pollution

Release of any pollutant into air is known as air pollution mainly caused by industrial emission (gasses like SO_2, NO_x, volatile organic compounds, particulate matters and heavy metals) [7], transportation (CO, NO_2) [14], agricultural activities (crop burning and using fertilizers release a large amount of NH_3, CH_4, CO_2, N_2O, SO_2, NO_x, VOC) [15], urbanization (rapid rise of industries, buildings, roads, waste treatments, residential heating or cooling produce high amount of SO_2, CO_2, Particulates, NO_2, and CO) [16], and

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natural sources (dust, ash, smoke, volcano eruption, forest fires and physical disasters release SO_2, NO_x, VOC, polycyclic aromatic hydrocarbons) [1]. Air pollution can lead not only many respiratory diseases like asthma, chronic obstructive pulmonary disease and high risk of lung cancer [17] but also cause cardiovascular diseases like hypertension, heart attack, stroke, atherosclerosis, systematic inflammatory responses, thrombosis, arrhythmia and vasoconstriction [18]. It also cause Alzheimer's disease, Parkinson's disease, chronic brain inflammation, multiple sclerosis, white matter abnormalities, microglia activation [19] and effect reproductive system as well [20]. Air pollution is the major factor for climate change [21], global warming [22], acid rain [23] and increase soil acidity [24].

Water Pollution

Water is the most important nutrient necessary for life of all ages [25]. Contamination of harmful chemicals to waterbodies including ocean, rivers, lakes and ground water due to industrial discharges mainly release heavy metals, ammonia, urea, phenolic compounds, perfluroalkyl acids, NaOH, hydrogen peroxide, formaldehydes, perfluorooctanoic acid [26], agricultural runoff that discharge animal waste, fertilizer, pesticides, herbicide, fungicide, [27], high amount of heavy metals [28], municipal wastewater [29] and mining [30] is called water pollution.

Water pollution is the major environmental pollution which leads more than 50 diseases and 50% child death annually [29]. According to world water development (WWD), every year 2–2.5 million people died due to diarrhea, 10 million deaths from cancer, 80,000 rectal cancer alone in US, 9.3% deaths from digestive cancer, 36,000 people from dengue, caused by poor water quality [29]. Except this, alone in Bangladesh 35 million people daily exposed to arsenic in drinking water [31]. Similarly, in Pakistan both ground water and surface water is mainly effected by pesticides, coliforms and toxic metals [32]. As reported by UNESCO in 2021, 80% industrial and municipal water is transferred into environment without treatment [29]. Industrial polluted water contains heavy amount of arsenic, lead, vinyl chloride and benzene, responsible for mutation, DNA damage, tumor, liver cancer, reproductive cancer, and gastric cancer [33, 34].

Soil Pollution

Soil is the mixture of organic matter (dead living organism), minerals, air and water, play important role for plant growth, food production and support life on earth [35]. Contamination of hazardous compounds in soil, which has a negative impact on ecosystem, human health and on agricultural productivity, produced by industrial activities released transition metals (lead, cobalt, zinc, chromium, nickel, cobalt, iron) [36], petroleum hydrocarbons, pesticides, biological pathogens [37], sulphate ions [38]; mining activities mainly produce toxic metals (mercury, lead, arsenic, cadmium, copper, chromium) [39, 40]; agricultural practices like fertilizer, pesticide, herbicide, animal waste release uranium, lead, radium, phosphates, nitrates and persistent organic pollutants [41]. Soil pollution cause soil erosion, degradation of ecosystem, loss of soil fertility, affect plant growth, contaminate drinking water and disturb aquatic habitat [42].

Plastic Pollution

Environmental pollution is the major problem of the modern times and plastic is one of the leading cause. Plastic has played a significant role in our lives but our ecology is in danger due to its excessive use [43]. More than one third of the total mass of plastics produced globally is used to make packaging, which is typically not recycled and ends up as waste. The excessive use of plastics has a considerable negative influence on the environment over time; it is estimated that 34 million tons of plastic are manufactured year, but only 7% of it gets recycled, with the other 93% being dumped into landfills and the ocean [44]. The materials that we commonly refer to as plastics are high molecular mass, synthetic organic polymers, primarily derived from hydrocarbons obtained from crude oil and natural gas [45]. The two main types of plastic are thermoplastic and thermoset [46]. The thermoplastic category includes materials like (high and low density) polyethylene (PE), polyethylene terephthalate (PET), polypropylene (PP), polyvinyl chloride (PVC), and polystyrene (PS), as well as "expanded polystyrene," while the thermoset category includes materials like polyurethane (PUR) and epoxy resins or coatings. When heated, thermoplastic can be repeatedly molded, whereas thermoset cannot be heated and remolded once it has been created. Plastics are typically generated from fossil fuels, but biomass (such as maize or plant oils) is being used more and more in their production. Once a polymer is synthesized, its properties remain the same regardless of the type of raw material used (i.e. PE will have the same properties, whether it is made from ethylene derived from fossil or biological sources) [47].

Plastic is mainly divided into different types among them single-use-plastic (SUP) is most common, important and widely used almost 50% of total plastic, used in packaging, bottles, bags, straws and cutlery, utensils [48, 49]. SUP contain bisphenol A, and persistent organic pollutants (POP) cause reproductive disorder, chronic diseases, developmental issue, immune system damage and endocrine disruption [50]. Another type of plastic is microplastic, tiny plastic particles having size less than 5mm, most toxic due to small size can be ingested and stored easily [51]. Microplastic mainly PS, PP, PE are used as microbeads in face wash, toothpaste, body wash, facial scrubs, cosmetics, and medical products, cause intestinal inflammation, asthma, oxidative stress, DNA damage, metabolic disorder, organ dysfunction, neurotoxicity and cancer [52–54].

Petroleum-based plastics have negative effects on the environment and society since they are not biodegradable and can release carcinogens when damaged or heated [55]. PVC [56] and PE [57] were two accidentally discovered new forms of plastics. In the early 1900s, formaldehyde and phenol were combined to create the first totally synthetic thermosetting glue, which Leo Baekeland dubbed Bakelite [58].

According to a rough estimation in 2019, 370 million tons annually produced and is continuously increasing that will be 445.25 million tons, among this more than 90% plastic cannot be recycled [59, 60]. Plastic is the biggest threat for environment, effect marine life [61], kill seabirds [62], contaminating aquatic ecosystem [63], affect plant fertility [64], respiratory health issue [65], climate change [45], release toxic gases [66] and increase carbon emission [67].

Over 99% plastic produced from non-renewable sources like fossil fuel [67], however researchers are now working on plastic production from renewable sources known as biodegradable plastic.

Bioplastics

Plastic prepared from plant or animal material is commonly known as bioplastic [68]. In pre-20th century people used cellulose, rubber and lignin extracted from grasses, agricultural waste, natural plant fiber and wood [69]. Bakelite and cellulose acetate were the 1st synthetic polymers prepared from natural sources with some chemical modifications in early 20th century for sunglasses, home furnishes, electronic devices, dresses, whistles, slip covers, cameras, and in some weapons [70]. In 20th century bioplastic like polylactic acid and polyhydroxyalkonates gained attention due to their cheapness, easy use and durability [71]. 2000–2010 was the commercialization period of bioplastic and many companies like NatureWork LLC produced bioplastics on large scale for stencils, biomedical applications and packaging [72].

Bioplastic also known as biodegradable plastic or biodegradable polymer, currently a new type of plastic, eco-friendly, cheap, degradable and recyclable, used mainly for packaging [73]. Bioplastic is mainly categorized into bio-based bioplastic and petroleum-based bioplastic [74].

Polyhydroxybutylate (PHB), the first bio-based bioplastic discovered in 1925 [75]. Except it, polyethylene succinate (PES), polyhydroxyalkonate (PHA), polybutyl succinate (PBS), polyethylene tertraphosphate (PET) and polyethylene furanoate (PEF) are other bio-based plastics commonly used [73]. Bio-based bioplastic can be synthesized by using waste biomass like jackfruit [76], waste banana peels [77], organic waste [78], agriculture waste [79], newspaper waste [80], oil palm empty fruit bunch [81], sugar cane [82], corn starch [83], potato starch [80], rice straw [84], rapeseed oil [85], cellulose and lignin from plants [86], bacteria [87], and Nano-fiber [88]. This bioplastic is easily degraded from bacteria [89–91], algae, and fungi [92], further both anaerobic/aerobic settings can facilitate the decomposition of bioplastics [93].

Petroleum based bioplastic, on the other hand is not degradable but can be prepared from petroleum or fossil fuels with some modification or addition of additives that facilitate faster degradation as compared to traditional plastic [94].

Properties of Bioplastic

Bioplastic is considered as unique, environmental friendly and attractive alternative to traditional plastic due to its properties. These properties vary depend on the composition of bioplastic. Some important properties of bioplastic are:

Biodegradability

Bioplastic can easily be degraded by enzymatic action, physical action, chemical reaction. Except these, bioplastic can easily be degraded by microbial action like aerobics, an-aerobics, archaebacterial, photosynthetic bacteria, fungi, present in soil, water at different environmental conditions (25–60°C, 50%–60% humidity and 7–8 pH) [95]. Due to this unique property bioplastic is best use as compared to petroleum plastics that retain in environment for hundreds of years.

Flexibility and Durability

Bioplastics are flexible and durable, can easily be bended, deformed and change shape without breaking [96] when exposed to mechanical stress, environmental effect, chemical exposure, UV radiation, pressure, temperature and aging factor [97]. This is an important property that enhance its application in different industries (packaging, medical devices, textiles and agriculture) to increase shelf life and decrease environmental impacts [98].

Transparency

Transparency is an important property when bioplastics are used in packaging, disposable items, or thin films [99]. Starch-based, cellulose-based, sugar-can-based and PHA are more transparent, can pass light without absorption or scattering [100]. Due to their transparency, these are widely used in food industry, labs, pharmaceuticals, electronics and automobiles [101].

Heat resistance

The ability of bioplastic to resist at high temperature without deformation, damaging or changing shape is called heat resistance of bioplastic, a crucial property when using in packaging, electronics and automobile components [102]. Starch-based bioplastics have more heat resistance (96.7 °C) than PLA (50–60 °C) [103].

Types of Bioplastics

As, bioplastic is plastic produced by renewable sources alternative to conventional plastic, today a wide variety of bioplastics are used, these types depend on source (raw material).

- Polysaccharides-based bioplastic
- Protein-based bioplastic
- Some aliphatic polyesters

Polysaccharides-Based Bioplastic (PSB)

These bioplastics are gaining popularity as sustainable alternatives to standard petroleum-based polymers due to low environmental effect and can be prepared by using natural material like cellulose, starch and chitin etc.

Starch Bioplastics (SB)

The second-largest agricultural product is starch. Currently, 2050 million tons starch produced from cereal and 679 million tons from roots annually [104] and 50% of bioplastic yearly produced from starch [105].

For conversion of starch into bioplastic, gelatinization is the important step, that involves heating of starch material with water so that granules absorb water, the H-bonds within the granules are ruptured to distort crystalline structure, after absorbing water starch molecules swell, become viscous or jelly like material [106]. Sometime plasticizers like sorbitol, glycol, and glycerol are added to enhance bioplastic characteristics [107]. The ratio of amylose to amylopectin significantly affects the characteristics of starch bioplastic. Higher amylose starch often has better mechanical qualities [108].

However, high moisture, gelatinize temperature, starch type (amylose concentration), plasticizer and time effect the property as well as use of bioplastic [109]. To increase mechanical properties and biodegradability of bioplastics PLA, PBS, PCL, PHA, PBAT are blended with starch [110]. SB are commonly used as packaging material due to low cost [111, 112].

Cellulose Bioplastics (CB)

Cellulose production is approximately 180 billion tons around the globe [113] and its bioplastic production will be 5.33 million tons in 2026 [114]. Cellulose bioplastic can be prepared by agricultural byproducts, pulp, softwood trees, plant material (rich in cellulose), bacteria, algae, fungi etc., [113]. The main components of cellulose bioplastics are cellulose ester like cellulose acetate, cellulose butyrate, nitrocellulose [115].

Polymerization is the most important step for bioplastic formation, cellulose monomers are joined to form polymer (cellulose ester) by using acetic anhydride or acetic acid [113]. CB show excellent biodegradability (40% degraded in five days) [116], high tensile strength, low density, low permeability [117], but can mix with PHA, PLA to improve mechanical properties, flexibility, non-toxicity, biodegradability and processing characteristics [118]. Such bioplastics are widely used in pharmaceutical, food, cosmetic, thermoplastic and automobile industry [119].

Protein Bioplastic (PB)

Different proteins from plant or animal source like casein, gluten, soy, collagen, can be used to produce bioplastics [120]. PB mainly used for packaging films and coating [121].

Some Aliphatic Polyesters

Aliphatic polyesters are frequently used due to versatility, biocompatibility, can be prepared from plant feedstock or microbial fermentation and are derivatives of aliphatic diols and dicarboxylic acids like PHA, PHB, PHV, PHH, PLA, PHU, PBS, PET. Small description of each is given below

Polylactic Acid (PLA)

PLA a glowing material synthesized by polymerization of lactic acid from starch, corn cassava, sugar beet or sugarcane via fermentation [122]. Due to its properties like good mechanical strength, biocompatibility, eco-friendly and biodegradability, these are used in 3D printing, medical devices, textile, packaging and disposable items [123].

Polyhydroxyalkanoates (PHA)

PHA can synthesize naturally by a variety of microbes, including those that ferment carbohydrates or fats [124]. In the natural world, microbes digest sugar or fats to form linear polyesters known as PHA. PHA is biodegradable and has characteristics that make it less elastic and more ductile than other polymers and have wide range of applications in biomedical, agriculture and food industry [125].

Polyethylene Terephthalate (PET)

Ethylene glycol (EG) and terephthalic acid (TPA) polymerize to form the polymer known as PET. PET is thermoplastic and contain 70% EG +30% TPA [126]. Although PET is primarily derived from fossil fuels and is not biodegradable but increase biodegradability and low cost PET can be synthesized from bio-based material like plant feedstock.

Due to low cost, transparency, and biodegradability PET is widely used as beverage bottles, food containers, straws, storage box [127]. PET accounts for over 16% of all plastic used in packaging in Europe.

Polybutylene Succinate (PBS)

PBS, also known as polytetramethylene succinate, is a thermoplastic polymer resin that belongs to the polyester family. An aliphatic polyester that is biodegradable and has qualities similar to polypropylene. One easy way to prepare PBS, a flexible semi-crystalline polymer, is to simply esterify succinic acid with 1,4-butanediol [128]. Nowadays, fermentation is used to produce succinate mostly from renewable resources. PBS is similar to petro-plastic due to flexibility, thermal stability, strength, and low cost make them highly useful in packaging films, agriculture (mulch films), automobile components, shopping bags [129].

Polyhydroxyurethanes (PHU)

According to studies, PHU sometimes is not considered as bioplastic but a synthetic plastic contains –NHCOO- (urethane linkage) produced by the reaction of polyols and isocyanates. Polyols can also be derived from renewable sources like plants oil, therefore it can also be known as bioplastic [130, 131]. Due to some properties like biodegradability (ability to break into small components by microbial action), mechanical properties (flexibility, elasticity, cannot deform easily), thermal stability (heat resistance), chemical resistance (resist to certain chemicals and solvents), cost, water absorption and biocompatibility PHU is considered better as compared to commercial plastics [132, 133]. PHU is excellent candidate for drug delivery system.

Poly-3-Hydroxybutyrate (PHB)

PHB is the type of bioplastic formed from plant starch/sugar by microbial action via fermentation [134]. PHB have low thermal stability, high degree of crystallization, non-toxic and commonly used in packaging, biodegradable, biocompatible, autocatalytic nature, easily recycled, low cost, improved mechanical behavior and thermoplastic [135].

Application of Bioplastics

As, bioplastic is biocompatible produced from renewable and biodegradable resources. Its production is continuously growing, has a wide range of applications due to their non-toxic nature, easy availability, biodegradation, flexibility and durability. These are widely used in our daily life now days in food container, packaging, kitchen ware, bottles, straws etc. Some significant applications are mentioned below:

Packaging

330 million tons annually plastic is produced world-wide and its 40% is consumed for packaging. Bioplastics have found widespread use in packaging materials for drinks, food and consumer goods, offering comparable characteristics to conventional plastics but originating from renewable sources [136, 137]. The main advantages to use bioplastics for packaging are to preserve food nutritional components, stop food decay and increased the shelf life of foods [138]. For packaging different types of bioplastics like PLA (films, straws, lids, pouches, bags, wrappers, pills, capsule, green house films) derived from plant source [139–141], PHA (food container, wraps, beverages, dairy products, cosmetics, seed covers, crop films) originate from bacterial fermentation of sugar or lipids [142–144], PBS (Packaging films, bags, trays, bottles) prepared by succinic acid and 1,4-butanediol [145] and starch-based (Food wrappers, shopping bags, trash bags, disposable cutlery, tableware) [111, 112].

Textile

The use of textile fiber is increased 100 million metric tons and continuously increasing as papulation increased; with natural fiber it is impossible to cover such a big consumption [146]. Bioplastics can be processed into fibers and commonly used in textile, alternative to synthetic fiber [137]. Improved breathability, reduced environmental influence, light weight, easy modifications like coloring, bleaching, cheapness and non-effectiveness against mice or other insects, PHA and PLA alone or their blends with natural fibers like jute, cotton, bamboo and widely used for clothes, carpets, non-woven fabrics [147, 148].

Agriculture

A number of benefits can be gained from the use of bioplastics in agriculture, including the reduction of carbon footprint. Biodegradable bioplastics, for example, degrade more rapidly and naturally, emitting organic molecules without harming the environment. Bioplastics are commonly used as mulch films [149] (to control weeds growth, maintain soil moisture, enhance crop quality), greenhouse films (control temperature and UV protection), seedling pots [150], seed coating [151] (increase germination rate, protection, control nutrients).

Medical and Drug Delivery

Due to environmental friendly nature, biocompatibility and biodegradability bioplastics like PGA, PLA, PHA, PLGA, PCL, PLLA and PCLA are used in medical for making surgical instruments [152], syringes [117], gloves, cups, trays and wound dressing [153].

Bioplastics are gaining attention in drug delivery system (DDS) due to their properties. Different bioplastics like PLGA converted into microparticles, nanoparticles [154]; chitosan into hydrogels [155]; cellulose biopolymers into films, coating [156]; and PHA into microspheres or nanoparticles [157] to encapsulate drugs.

Cosmetics

Nowadays, Biopolymers also used in Cosmetics and beauty products such as thickeners, conditioners, binders, active Ingredients and sensory materials. PHAs are commonly used material in cosmetology, although its production is expensive but they are mix with other biopolymers such as starch or PLS to make less expensive [137].

Electronics

Bioplastics like PHA (making electronic components), PCL (making flexible components, phototypes, sensor) and PEF (producing complex electronic components, pack electronic devices, improve mechanical support to devices) [158].

3-D Printing

Bioplastic has practical applications in 3D printing like in medical sector to design medical devices, anatomical models, and customized prostheses. PLA, PCL, PLGA due to non-toxic nature used in medical applications, tendon and skin regeneration [159, 160]

Automobile Industry

As, an alternative to petroleum based plastic bioplastic is used for making internal automobile components [161] (dashboards, storage components, headrests, automotive seats), engine components [162] (fuel lines, electronic connectors), CB due to light weight used as external automobile components [162] (bumpers, door trims, body panels) [119].

CONCLUSION

In conclusion, bioplastics are a sustainable and environmentally friendly alternative to traditional plastics. We've highlighted a variety of biodegradable polymers for 3D printing, packaging, and biomedical devices that are biodegradable. In contrast to conventional plastics, bioplastics are renewable and biodegradable. Additionally, bioplastics are improving mechanical properties and expanding their applications due to advancements in technology. Despite significant progress, bioplastics still face challenges, such as scalability, cost-effectiveness, and end-of-life management. In order to overcome these obstacles and to promote widespread adoption of bioplastics, further research and innovation are needed. In order to facilitate the transition to a circular economy, academia, industry, and policymakers must collaborate. Using bioplastics reduces plastic pollution, mitigates climate change impacts, and promotes sustainability. Aside from preserving our ecosystems, bioplastic alternatives can also improve the resilience of our planet and safeguard our future generations.

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.

USE OF AI FOR WRITING ASSISTANCE

Not declared.

ETHICS

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

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Review Article

A review of air pollution and ethical consumption behavior due to fragrances

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ABSTRACT

This paper presents a comprehensive review of literature focusing on the detrimental effects of fragrances on air quality. While previous studies traditionally attributed air pollution to sources like automobile emissions or industrial discharge, this study delves into the impact of consumer products, particularly fragrances, on both indoor and outdoor air pollution. Through a systematic review of existing research utilizing databases such as Web of Science, Google Scholar, and Scopus, the study synthesizes findings regarding the composition of fragrances, regulatory practices related to ingredient labeling, and public awareness regarding the link between air pollution and fragrances. The findings indicate that the ingredients used in perfumes can contribute to air pollution and respiratory ailments, underscoring the need for stringent regulations. Despite this, there is a lack of comprehensive labeling requirements for perfume products worldwide, which may contribute to limited consumer awareness regarding the association between air quality and fragrances. Given the intimate relationship between air pollution and human well-being, this study underscores the importance of exercising caution in the use of household consumer products such as perfumes and air fresheners to mitigate their impact on air quality.

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INTRODUCTION

Contemporary society is replete with fragranced consumer goods spanning perfumes, air fresheners, soaps, hand sanitizers, laundry detergents, and personal care items [1]. The global fragrance market was valued at $50.85 billion in 2022 and is projected to reach $53.77 billion by 2023, driven primarily by heightened consumer expenditures on premium and exotic scents alongside improving socioeconomic conditions. Perfumery has become an essential commodity, emblematic of the expanding personal care sector, which is increasingly intertwined with individuals' self-assurance and poise. Sales growth in the market is further propelled by innovative responses to consumer preferences, such as L'Oréal's Jo Malone boutiques offering tailored fragrance consultations and bespoke blending services, alongside distinctive packaging designs featuring cityscape artwork by on-site artists, as witnessed in their Tokyo establishment [2]. Europe commands a substantial 34% share of global revenue within the fragrances sector, closely trailed by the Americas with a 32% market dominance. Remarkably, expenditures on fragrances are witnessing a notable surge in these developed, affluent regions. Consumers perceive fragrances as a source of emotional upliftment, facilitating the evocation of cherished memories and pleasant experiences. This sentiment resonates particularly strongly among younger demographics, who exhibit heightened engagement in fragrance consumption and a willingness to invest

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considerably in scents that resonate with their preferences. Insight from a survey utilizing Prime Target's social media analytics tool reveals a burgeoning interest among consumers in fragrances featuring natural, organic, and vegan ingredients, as evidenced by the heightened search activity surrounding these descriptors [3]. Building upon these insights, we undertake an examination of the ramifications of perfumes on both indoor and outdoor air quality as well as human health—a topic that has received limited attention in current scholarly discourse. This review seeks to elucidate the manner in which chemicals present in personal fragrance items, notably perfumes, influence environmental pollution dynamics and human well-being.

MATERIALS AND METHODS

This review updates the state of research focusing on the impact of ingredients in fragrance products, including perfumes, on indoor and outdoor air pollution in order to reduce air pollution associated with climate change. The literature review was conducted between March 2 and March 11, 2024. This review aims to introduce and elaborate on the contained air pollutants in fragrance products, including perfumes. In general, the study of air pollution as a whole and the study of individual components require different approaches and focuses in environmental science. Studies investigating air pollution differ in that they can provide a broad overview of general air quality and its potential impacts on human health and the environment by considering all substances and assessing the overall air quality comprehensively. In contrast, studies that focus on individual components of air pollution narrow the scope of the study to a specific pollutant or group of pollutants. An example of this is analyzing the major constituents and volatile organic compounds in perfumes and fragrances and examining their effects individually. This provides an in-depth understanding of the nature of specific pollutants and is useful for regulatory purposes or policy formulation. Also, it aims to draw attention to indoor and outdoor air pollution caused by chemicals in fragrance products as the consumption of scented consumer goods such as perfumes becomes more specialized and increasing. Below we describe in detail our search strategy, article selection methods, and data synthesis procedures.

Search Strategy

For this review, six databases in the natural sciences, social sciences, environmental engineering, management, and consumption were searched according to PRISMA flow guidelines: PubMed, Scopus, Medline, ResearchGate and Google Scholar using the search terms (a) 'perfume consumption' and 'premium fragrances' (b) 'volatile organic compounds' (c) 'air fresheners' and 'air pollution'. The literature search was conducted through a broad search strategy using the following keywords Environmental pollution; air pollution; air pollutants; nitrogen dioxide; carbon monoxide; sulfur dioxide; nitrogen oxides; ozone and volatile organic compounds; dioxins; organic pollutants; cadmium; lead; mercury; heavy metals; fragrance products; exhaust; fragrances; respiratory health; respiratory diseases; chronic diseases; reduced lung function; perfume ingredients; fragrance product ingredients; indoor air pollution; indoor air pollutants; fragrance substances; limonene. The literature search strategy and review process according to the PRISMA 2020 flow rules can be seen in Figure 1. In addition, the search for recent literature (published between 2019 and 2024) included specific keywords (air pollution and air pollutants): Volatile organic compounds, bioaerosols, formaldehyde, airborne constituents, atmospheric compounds, air quality index, sensitive receptor areas, air environmental pollution, emissions, air pollution monitoring, air pollution control, air pollution mitigation, climate change impacts of air pollution, urban air pollution, Air Pollution and Outdoor Air Quality, Air Pollution and Health Disparities, Air Purification Devices, Vehicle Emissions and Air Pollution, Air Pollution Modeling, Perfumes and Air Pollution, Perfumes and Indoor Air, Fragrances and Air Pollution, Fragrances and Air Pollutants, Fragrances and Indoor Air Quality, Indoor Air Quality.

Eligibility Criteria

Articles included in this review had to meet the eligibility criteria for this review, which included selecting studies related to the characteristics of fragrance consumption, fragrances and indoor air pollution, types of air pollutants, volatile organic compounds, and fragrance products and air pollution: Negative effects of increased fragrance consumption, indoor air pollution impacts of fragrances, air pollution impacts of fragrances, air pollution linkages between fragrance products and air pollution, air pollution caused by increased fragrance product consumption, long-term strategies for air pollution caused by fragrance products, environmental preferences of fragrance consumers, relationship between environmental values and fragrance consumption, strategies for reducing fragrance product consumption to prevent air pollution, and the role of ethical consumption in preventing air pollution.

Screening and Data Extraction

Articles were included in the corpus if they (1) examined the expansion of the fragrance market and increased sales, (2) addressed the link between fragrance products and air pollution, (3) addressed volatile organic compounds, (4) addressed the impact of fragrance products on indoor and outdoor air pollution, (5) were peer-reviewed, and (6) were journal articles or conference presentations.

We excluded articles that (1) did not examine the consumption of perfumes and fragrance products, (2) did not examine the link between fragrance products and air pollution or environmental pollution, or (3) did not examine volatile organic compounds.

We considered different types of articles, including original articles, full-text articles, internet articles, summary reports, and series, and did not impose restrictions on publication date or language. Exclusion criteria included inaccessible full text, full text without raw data, inappropriate topics, and doctoral dissertations, which were searched through the ProQuest Dissertations and Theses Global Database.

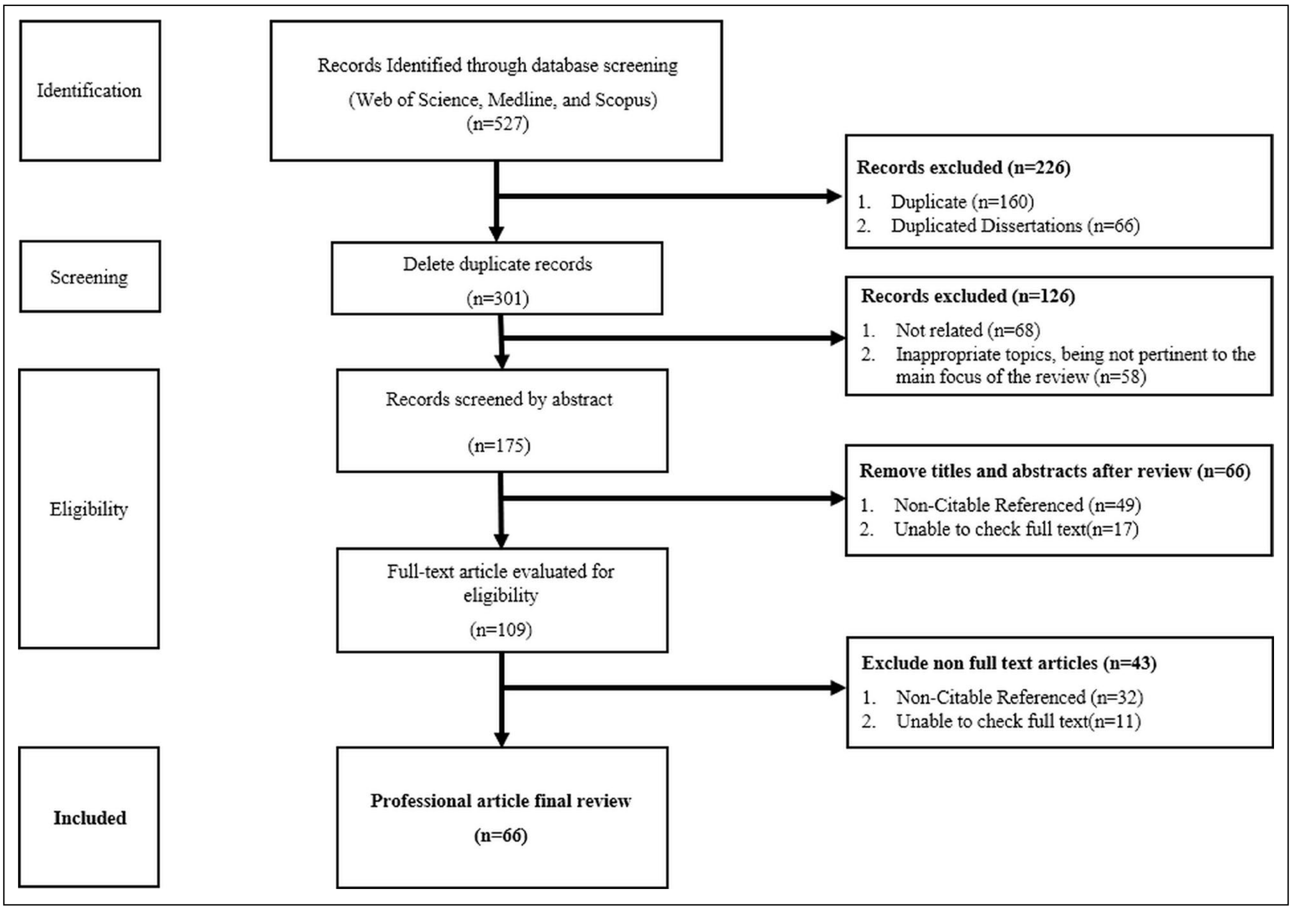

Figure 1. PRISMA flow chart for literature review search results.

Study Selection and Data Extraction

Of the citations from the articles reviewed in the primary search, additional references were identified through a manual search and assessed for eligibility by reviewing titles and abstracts. Articles that did not meet the inclusion/exclusion criteria were then excluded from this review. Finally, we reviewed the full text of the articles to determine inclusion of the remaining articles and excluded those that did not meet the criteria. The 65 articles included in this review were proposed under the following titles: "Air pollutants, the potential for increased perfume consumption", "Fragrance product ingredients contributing to air pollution", "Sustainable consumption to prevent air pollution from fragrances", "Ethical consumption strategies to prevent air pollution; reducing consumption of fragrances and personal fragrance products", "The impact of fragrances and fragrance products on overall air pollution", "Air pollutant induction and chronicity from fragrances", and "Limitations of the current review and future research". In the final stage, a total of 527 articles were selected, with publication dates ranging from 2004 to 2024. The model diagram of this study was organized as shown in Figure 2.

The main findings of the study are that the increased use of fragrances and fragrance products has a detrimental effect on air pollution levels, and the negative association between the consumption of these products and indoor and outdoor air pollution levels is significant. The main findings consistently emphasize the adverse effects of organic chemicals and ingredients in fragrances and fragrance products on air pollution, with particular emphasis on increased indoor air pollution levels.

FRAGRANCE CONSUMPTION AND AIR POLLUTION

Perfume-Making Substance

The primary purpose of perfume is typically to impart a pleasant scent, often employed for the purpose of obscuring or camouflaging malodorous odors [4]. Nevertheless, essential oils, prevalent in personal care items for their aromatic properties, contribute significantly to volatile organic compound (VOC) emissions derived from fossil fuels, constituting approximately half of such emissions [5]. Essential oils, encompassing well-known varieties like lavender, orange, eucalyptus, and tea tree, are extensively utilized across cosmetic, fragrance, and aromatherapy domains. However, these oils represent intricate blends containing diverse chemical constituents, notably terpenes, with each essential oil emitting at least one volatile organic compound (VOC) categorized as potentially hazardous [6]. Among 104 frequently utilized flavor products, limonene emerged as the predominant volatile organic compound (VOC), present in 77% of these items. These VOCs constitute a significant portion of pollutants implicated in detrimental impacts on both air quality and human well-being. Notably, 68 VOCs identified among the analyzed flavored products were

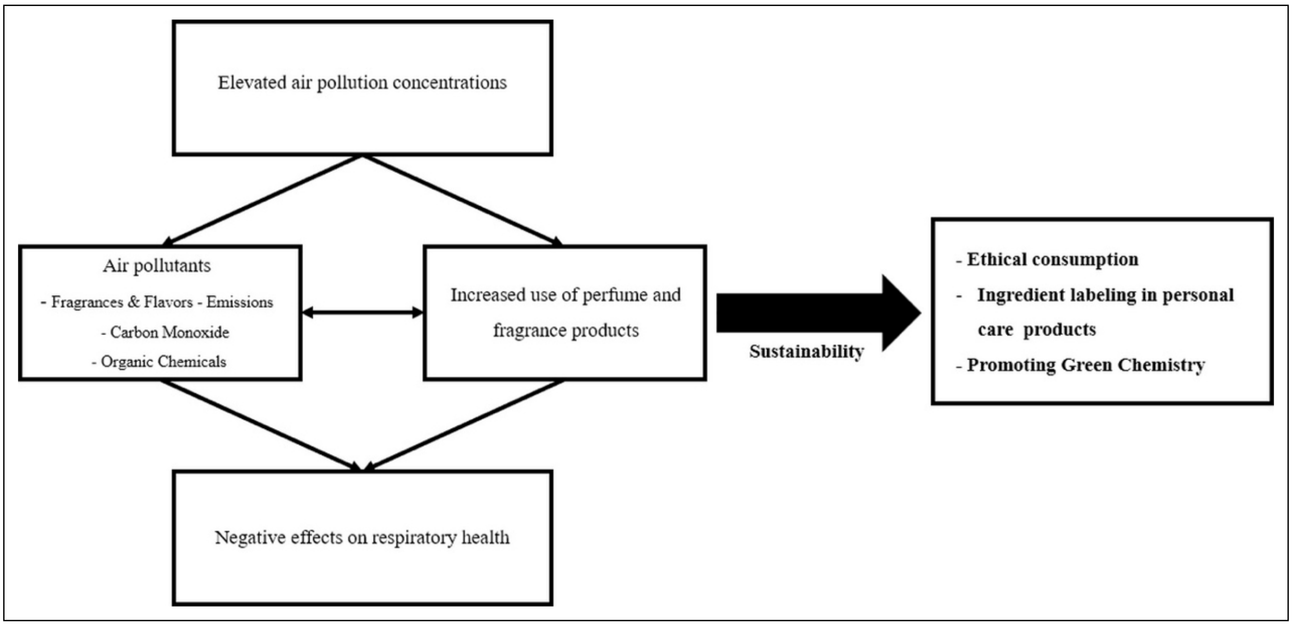

Figure 2. Model diagram of our study.

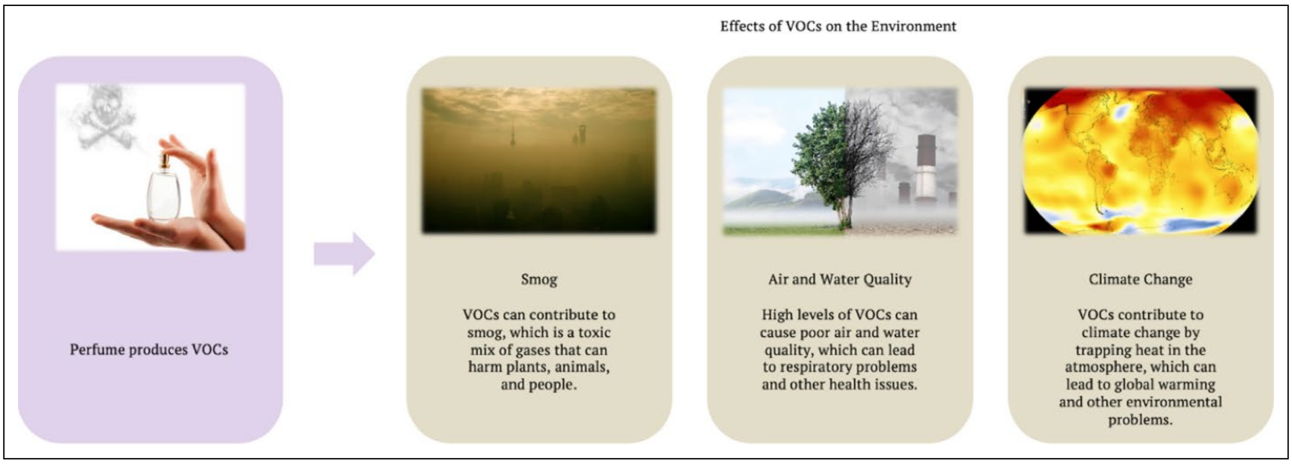

Figure 3. Environmental pollution caused by perfume consumption [20]. Perfumes are consumer goods made from potentially hazardous chemicals.

classified as potentially hazardous. Their interaction with ozone can lead to the formation of hazardous byproducts, including formaldehyde and acetaldehyde [7]. However, the majority of components constituting fragrant consumer goods remain undisclosed to consumers [4]. Furthermore, essential oils enjoy exemption from mandatory ingredient labeling requirements when marketed individually, thereby contributing to a dearth of information concerning the potential hazards associated with volatile organic compounds (VOCs) and essential oils found in perfumes [8]. Consequently, individuals may find it challenging to perceive certain compounds within perfumes as hazardous and to recognize the connection between perfume usage and environmental contamination (Fig. 3).

To investigate this, we assessed societal consumption patterns and perceptions regarding the potential health impacts of fragranced household and personal care products. The findings revealed that most participants utilize both fragranced and unscented household and personal care items, with one-third of these individuals and their families experiencing respiratory or dermatological allergies. Although the majority are cognizant that fragranced household and personal care products can provoke respiratory and skin allergies, there is a lack of awareness regarding which specific fragrance substances act as potential allergens for the skin and respiratory system [9]. Indeed, for numerous consumers, the presence of fragrances can significantly influence their engagement in public activities. Approximately half of individuals sensitive to scents have avoided certain locations to prevent exposure to fragrances. Conversely, some scent-sensitive individuals exhibit a preference for fragranced products and environments. Half of the scent-sensitive population report using perfume to enhance their attractiveness, while about half of the general population indicated they would refrain from using scented products if they were aware these products emit harmful air pollutants. These responses highlight the various factors influencing risk perception and safety behaviors. Survey data indicated that in Germany, an average of 7.4 working days per person were lost due to illnesses attributed to exposure to fragranced products in the workplace, with an estimated economic cost of $14.5*10^9$ euros annually. This underscores the importance of effectively communicating the risks associated with fragranced products [10]. In conclusion, it's noteworthy that volatile organic compounds (VOCs) typically exist in significantly elevated concentrations within enclosed spaces where perfumes are applied. Undoubtedly, consumer products mimicking perfume scents serve as the primary source of indoor VOCs, thereby being categorized as contributors to air pollution [11–13].

A Health Problem Caused by Fragrances

Findings indicate that exposure to air pollution ranks as the fifth most significant risk factor for human health on a global scale, trailing behind malnutrition, dietary risks, high blood pressure, and tobacco usage [14]. Although fossil fuels remain an important factor in air pollution in cities, exposure to PM2.5 is increasing from chemicals [15]. On average, 32.2% of adults across four nations report experiencing scent sensitivity, characterized by adverse health reactions upon exposure to fragranced consumer products like perfume. Within sub-groups exhibiting below-average health conditions, the prevalence of scent sensitivity is notably elevated. For instance, among individuals diagnosed with asthma, 57.8% report experiencing adverse effects from fragranced products, while among those with autism, the figure rises to 75.8% [16]. Beyond perfumes, inhalation of fragrant emissions stemming from laundry products, such as fabric softeners boasting diverse scents, is correlated with detrimental health outcomes including asthma exacerbations and migraines [17]. Specifically, exposure to D-limonene, one of the predominant limonene compounds found in fragrant products, is associated with adverse effects on the skin and eyes, as well as respiratory symptoms such as wheezing and coughing [18, 19]. Asthma stands as a prevalent chronic ailment, and given limonene's utilization in the production of personal care items like perfumes and household cleaners, exposure to this compound is widespread. Consequently, in-home exposure to limonene could potentially elevate the incidence of asthma within the broader populace. Depending on the extent of contact, limonene adversely impacts dermatitis, airway reactivity, and various respiratory health metrics [20]. Empirical studies conducted in real-world settings have demonstrated that using essential oil diffusers in enclosed spaces can significantly contribute to the levels of terpene VOCs indoors. The concentration of emissions from these diffusers can influence indoor air quality over durations ranging from 5 hours to 60 days, depending on whether transient or continuous devices are used. Specifically, in terms of consumer exposure to evaporating essential oils within indoor environments, transient diffusers can release emissions as high as 100 mg/h per gram of product over short periods, generally around 1 hour. In contrast, continuous diffusers release lower concentrations of terpenes, approximately 5 mg/h per gram of product, but extend over much longer periods, often spanning several days. Therefore, transient diffusers are linked to acute exposure episodes, whereas capillary diffusers can lead to prolonged, chronic exposure [21]. A study entitled "Fragranced Products Emit a Bouquet of VOCs," based on a different experimental investigation, identified over 100 VOCs in numerous "green," "natural," or "organic" PCHPs. More than 20 of these VOCs were categorized as "toxic" or "harmful," yet only one product listed any of these substances on its label. The predominant VOCs detected included terpenes (such as limonene, α- and β-pinene), ethanol, acetone, acetaldehyde, as well as carcinogenic compounds like 1,4-dioxane, formaldehyde, and methylene chloride. Measurements taken in a well-ventilated room of 50 m^3 demonstrated that the levels of d-limonene, dihydromyrcenol, linalool, linalyl acetate, and beta-citronellol emitted from cleaners and air fresheners containing terpenoids and glycol ethers were significantly higher (~35-180 mg/day over 3 days) compared to their concentrations in the air (average air concentration ~30–160 $\mu g/m^3$) [22, 23]. Glycol ethers are recognized as regulated toxic air pollutants, and terpenes can interact with ozone to produce secondary pollutants [24].

Poor air quality exerts a significant influence on an individual's emotional well-being, with severe levels of air pollution correlating with diminished human happiness [25–27]. Weather patterns and the scheduling of significant events during holidays or weekends are likewise associated with the collective happiness levels of urban residents [28]. During periods of elevated air pollution, individuals sensitive to environmental contaminants tend to gravitate towards indoor pursuits, such as increased engagement with social media platforms, as opposed to outdoor activities, which may involve tasks like grocery shopping. Consequently, research indicates a higher likelihood of opting for food delivery services over dining out on days characterized by poor air quality. This shift towards food delivery reduces exposure to outdoor environments, as individuals opt to have meals delivered to their workplaces or residences. Indeed, air pollution impedes individuals' mobility and diminishes their inclination to venture outdoors. Particularly in urban centers within developing nations, consistent poor air quality serves as a significant driver prompting consumers to rely on food delivery services as a preferred dining option [29–32]. This phenomenon establishes a detrimental cycle, as heightened reliance on food delivery services in response to high air pollution levels contributes to increased waste generation, thereby exacerbating environmental pollution. Collectively, elevated air pollution levels correlate with diminished citizen happiness and adverse impacts on emotional well-being, underscoring the societal costs associated with air pollution [33].

Two Faces of Perfume Calling for Sweet Danger

For millennia, fragrances have been employed to enhance the appeal of products, creating aesthetically pleasing environments and satisfying user preferences. However, despite rigorous safety evaluations conducted on products containing these scents, recent findings have revealed their association with adverse impacts on air quality [34]. First, fragrant consumer products such as perfumes can be a major cause of indoor air pollution [35]. Across global indoor environmental studies, aromatic chemical compounds, such as limonene, consistently emerge as prevalent pollutants found at elevated concentrations [13, 36, 37]. These compounds are not only implicated in indoor air pollution but also contribute to outdoor air quality degradation. Fragrance products utilized indoors ultimately disperse outdoors, exerting an impact on the surrounding air quality through their emission capabilities [38]. In a confined space, it can influence air quality by altering the concentration of particular volatile organic compounds within the atmosphere. Indoor air quality serves as a crucial determinant of residents' comfort, health, and cognitive performance, with certain airborne constituents originating from external sources [39].

The primary objective of fragrances, particularly those employed within households or enclosed spaces, is to impart a pleasant aroma to the air, thereby intentionally introducing a mixture of chemicals indoors and potentially compromising indoor air quality. Household scents may also emit compounds such as ethanol, iso-propanol, dipropanol, dipropylene glycol, and numerous other solvents. Consequently, eliminating air fresheners, perfumes, and scented candles can enhance overall indoor air quality. To foster a clean and healthy indoor environment, it is more advantageous to implement frequent ventilation, utilize vacuum cleaners equipped with HEPA filters, and ensure regular maintenance and cleaning of air purifiers [40].

A 2018 study conducted in Los Angeles, USA, investigated atmospheric chemicals and identified volatile organic compounds (VOCs) emitted from consumer products such as perfume, paint, and ink as significant contributors to air pollution, comparable to emissions from automobiles. These VOCs are recognized as primary precursors in the formation of smog and ozone, as well as fine particulate matter in the atmosphere. However, the consumer market for fragrances and other scented products is growing (Fig. 4). In Los Angeles, approximately 42% of fine particulate matter, known to pose serious respiratory health risks, originates from consumer products. This finding underscores the impact of consumer goods, such as perfume and paint, which are formulated for pleasant fragrance or designed to evaporate upon production [41].

Moreover, the production of consumer goods like perfumes contributes significantly to the accumulation of packaging waste, particularly plastic, a commonly utilized material known for its detrimental environmental impact. As the fragrance consumer market expands, there arises a heightened imperative for embracing eco-friendly practices in product design and packaging. Companies operating within the fragrance industry ought to prioritize sustainable product design, encompassing the selection of packaging materials that not only exhibit aesthetic appeal but also adhere to principles of reuse, recycling, and remanufacturing. Such sustainable practices are integral to addressing societal objectives and fostering environmentally responsible consumption patterns [42, 43]. Table 1 provides a concise overview of the potential benefits and difficulties associated with the use of fragrances, particularly in relation to their environmental impact.

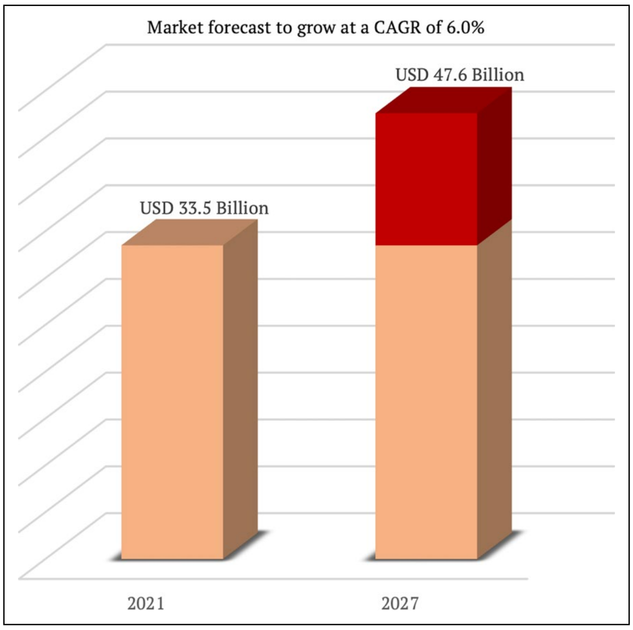

Figure 4. An increase in the perfume market [3]. Growing interest in personal care is driving fragrance consumption.

Sustainable chemistry is characterized as an approach to chemical development that prioritizes safer and more environmentally conscious practices, addressing the economic and social ramifications of chemicals throughout their life cycle. This concept spans various sectors, including water, energy, food, climate, and population, and significantly contributes to human health and biodiversity conservation. In contrast, green chemistry focuses on guiding chemists to synthesize chemicals through eco-friendly and highly efficient processes, aligning with fundamental science principles pertinent to the Sustainable Development Goals (SDGs). Key measures, such as promoting green chemistry in the manufacture of fragrances and their constituent chemicals, enhancing public awareness, and implementing stricter environmental regulations, will be crucial for future policymakers overseeing personal care products, including fragrances [44].

RESULTS AND DISCUSSION

Regulatory Status and Proposals for Personal Care Products (Fragrances, Air Fresheners, Etc.)

Phthalates, commonly employed as additives in cosmetics and everyday essentials, are incorporated into cosmetics and personal care items in substantial quantities. Regular usage of these products results in a rapid elevation of phthalate monoester levels in urine. These additives are prevalent in cosmetic formulations, including perfumes and nail care products [45]. Therefore, it can be said to be a substance that affects not only human health but also air pollution.

The attribution of responsibility for climate change is often correlated with economic advancement, particularly evident

Table 1. Potential benefits and challenges associated with fragrance use

Opportunities	Challenges
Increased Consumer Awareness: Growing awareness about the environmental impact of fragrances can lead to more informed consumer choices.	**Volatile Organic Compounds (VOCs):** Many fragrances emit VOCs, which contribute to air pollution and can cause health problems.
Development of Eco-Friendly Products: The demand for eco-friendly and natural fragrances can drive innovation in sustainable product development.	**Regulatory Compliance:** Ensuring that fragrances meet environmental regulations can be challenging and costly for manufacturers.
Market Growth for Natural Products: The market for natural and organic fragrances is expanding, offering economic opportunities for businesses.	**Lack of Standardization:** The absence of standardized guidelines for labeling and marketing eco-friendly fragrances can confuse consumers.
Health Benefits: Using natural fragrances can reduce exposure to harmful chemicals, promoting better health outcomes.	**Cost of Sustainable Ingredients:** Natural and eco-friendly ingredients can be more expensive, leading to higher product prices.
Reduction in Synthetic Chemical Use: Encouraging the use of natural ingredients can decrease reliance on synthetic chemicals that contribute to air pollution.	**Performance and Stability Issues:** Natural fragrances may have shorter shelf lives and less stability compared to synthetic alternatives.
Corporate Social Responsibility (CSR): Companies can enhance their CSR profiles by adopting sustainable practices in fragrance production.	**Consumer Skepticism:** Some consumers may be skeptical about the effectiveness and quality of eco-friendly fragrances.
Technological Advancements: Innovations in green chemistry can lead to the development of new, less polluting fragrance compounds.	**Supply Chain Constraints:** Sourcing sustainable raw materials can be challenging and may disrupt supply chains.

in affluent developed nations reliant on carbon-based economies. Consequently, these nations are typically assigned greater accountability for climate change due to the incidental consequences of their prosperity. This acknowledgment of responsibility fosters a sense of interdependence among individuals concerning social issues, prompting many to undertake measures aimed at curbing their own economic progression to mitigate potential adverse impacts on their community or collective [46]. Indeed, the consumption and market scale of perfumes are substantial in developed nations. John Broome, a philosopher and economist, posits that addressing climate change will necessitate the reduction of greenhouse gas emissions, predominantly from individuals within the more affluent segments of society, reflecting the global impact of their actions [47]. Undoubtedly, climate change presents inherent complexities, stemming from both internal dynamics and external influences. As we increasingly recognize the gravity of the climate crisis and endeavor to address it, the responsibility for mitigation rests collectively upon all of us. To this end, it is imperative to mandate the disclosure of general terms or ingredients used in fragrance formulations. While current regulations necessitate the listing of ingredients for personal care and cosmetic products on product labels, fragrance-related constituents are not required to be disclosed on Material Safety Data Sheets (MSDS) [48]. This is a factor that consumers are aware of perfume or fragrant substances, so it should be changed for a change in consumption behavior. Disclosing all ingredients in personal care products, such as fragrances and air fresheners, can enhance consumer protection and promote sustainable consumption. Regulatory authorities can guide the industry on providing safety information about product ingredients through various approaches: (1) listing all ingredients on the product label, (2) listing only key ingredients on the product label, (3) displaying all ingredients on the manufacturer's website, or (4) listing key ingredients on the product label and additional ingredients on the website. Each approach has its own merits and drawbacks in informing consumers about the constituents of fragrances and fragrance products. Moreover, risk communication forums that consistently address the environmental and health impacts of these products can effectively foster understanding of chemical information, toxicological science, regulatory guidelines, labeling practices, and consumer concerns [49].

Regulations for personal care products, including cosmetics, vary significantly across different regions, posing challenges for global compliance. Efforts have been made to harmonize regulatory frameworks to facilitate international trade. In the European Union (EU), all member states adhere to a unified regulatory framework under Regulation (EC) No. 1223/2009, overseen by the European Commission, which replaced the earlier Directive 76/768/EC. This regulation aims to standardize cosmetic regulations across the EU and incorporate technological advancements. However, such harmonization has not been universally achieved [50]. In contrast, the United States relies on the Federal Food, Drug, and Cosmetic Act (FD&C Act) of 1938 and the Fair Packaging and Labeling Act (FPLA) of 1966, regulated by the Food and Drug Administration (FDA) [51]. These laws have seen minimal amendments since their inception. Similarly, Canada's regulatory landscape is governed by the Cosmetic Regulation Act of 1977 and the Food and Drugs Act of 1985, which have also undergone only minor updates [52]. Brazil's regulatory structure for cosmetics involves three main bodies: the Ministry of Health, the Brazilian Health Regulatory Agency (ANVISA), and the General Directorate of Hygiene, Perfumery, Cosmetics, and Sanitary Products (GHCOS). These organizations operate through a series of resolutions that have been periodically revised to address regulatory needs [53]. This disparity in regulatory evolution across regions underscores the challenges of achieving global regulatory harmonization in the cosmetics industry [54].

There is Ethics in Incense

The growing awareness of environmental impacts and the trend towards healthier consumption patterns have driven the popularity of eco-friendly products, including cosmetics made from natural ingredients without chemical additives [55–58]. Typically, eco-friendly or green cosmetics and personal care items encompass products such as skincare, body care, hair care, oral care, color cosmetics, and toiletries that utilize natural and organic ingredients. These products often come in environmentally friendly or reusable packaging and emphasize the exclusion of synthetic chemicals [59]. As consumers gain more awareness about the health and hygiene benefits of cosmetics and personal care products, they are increasingly opting for natural and organic options, which are considered safer alternatives due to the potential side effects of conventional products [60]. Additionally, the global demand for safe, healthy, and clean cosmetics and personal care products has surged, particularly in the wake of the COVID-19 pandemic [58]. This shift in consumption is known as sustainable and ethical consumption. Consequently, the rising demand has spurred international cosmetics companies to create more products featuring natural ingredients and to expand their natural product lines [58, 60]. As a result, the global market size for natural and organic cosmetics grew from $34.5 billion in 2018 to $36.3 billion in 2019, with projections estimating it will reach $54.5 billion by 2027 [61].

Also, opting for unscented products presents a viable approach. Unscented alternatives can effectively fulfill the same functions as conventional fragranced products, albeit without the associated potential issues linked to scented formulations. For instance, fragrance-free cleaning or disinfecting products offer comparable efficacy without the inclusion of added fragrances [16]. Unscented products can be a simple and effective approach to reducing air pollution and potential health risks [17]. It should be noted that fragrance-free and fragrance-free products are different. The fragrance-free product may be added with a fragrance to cover the odor of other components [62].

Furthermore, it cannot be assumed that customers or the general populace inherently favor scented environments. Moreover, individuals would likely refrain from using fragranced products if they were aware of the potential release of harmful air pollutants. Ethical consumption should not be hindered by unfamiliarity with certain practices or products [63]. Perfume, being a luxury item and a means of self-expression within consumer culture, often entails excessive packaging. Ethical consumption entails adhering to consumption practices that minimize the use of plastic and reduce waste, recognizing the detrimental effects of such practices on the common good. Human ingenuity is adept at devising sustainable solutions, and the realization that ethical consumption is not inherently burdensome enables the design of systems that harmonize with both human needs and environmental preservation [64].

Research has shown that scented products, such as perfumes and air fresheners, contribute significantly to indoor air pollution by emitting volatile organic compounds (VOCs). These emissions can react with ozone to form secondary pollutants such as formaldehyde and ultrafine particles, which can pose health risks and contribute to overall air quality degradation. For example, studies have shown that air fresheners and other scented products emit a variety of VOCs, including terpenes such as limonene, which can form harmful byproducts when they interact with indoor ozone, which highlights the need for stricter regulation and increased consumer awareness of the use of these products and their environmental impacts. A comparative analysis of regulatory frameworks also reveals significant differences in how regions address this issue. The European Union has made significant progress in harmonizing cosmetic regulations to enhance safety and market consistency through Regulation (EC) No. 1223/2009, while the United States and Canada still operate under outdated legislative frameworks with minimal amendments, posing challenges to harmonization and comprehensive risk communication [65]. Integrating these perspectives can provide a more robust analysis of the impact of increased fragrance use on air pollution and highlight the need for global regulatory consistency and public education on the environmental and health impacts of fragrance products. By effectively adopting these changes in ethical consumer behavior, the European Union (EU) is projected to achieve a reduction in its carbon footprint by approximately 25%. The most significant contributions would stem from altering consumption patterns (28% of the total), decreasing overall consumption (26%), transitioning to products with a lower carbon footprint during production (17%), and opting for goods that emit fewer carbon emissions during use (19%) [66].

CONCLUSION

The climate crisis impacts every industry, with air pollution intricately linked to both our emotional well-being and outdoor activities. Among the significant contributors to air pollution are perfumes and air fresheners, which serve multifaceted purposes such as self-expression and mood enhancement. Despite their increasing market demand, many perfume ingredients comprise potentially harmful chemicals, posing threats to both indoor and outdoor air quality and overall health. Furthermore, the production, transportation, use, and disposal of fragrance products generate environmental pollutants and contribute to resource waste through excessive packaging materials like glass, plastic, and paper. The lack of ingredient disclosure to consumers further exacerbates the risks associated with fragrance use. Thus, mitigating unnecessary fragrance consumption and ensuring the use of unscented, ethically sourced ingredients becomes imperative in promoting environmental sustainability and safeguarding public health.

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.

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Not declared.

ETHICS

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

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Review Article

Temporal changes in water quality in Leh Ladakh region: Impact of urbanization

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ABSTRACT

Water is a valuable and limited resource in semi-arid regions like Ladakh. Effective management and conservation of water are crucial to prevent negative consequences on the area's quality of life. Since becoming a Union territory, Leh, a district of Ladakh, has undergone rapid urbanization due to its administrative status, air service facilities, tourism, and increasing population. However, this urbanization and tourism boom have resulted in a higher demand for water and a decline in its quality. Glacial-fed water is the primary source for drinking and agriculture in Ladakh. As Ladakh has become a popular tourist destination, the distribution and quality of water have been negatively affected. Construction of hotels and guest houses on agricultural lands, could further harm Ladakh's fragile ecological environment. Due to the challenging terrain and harsh conditions, there has been limited research on water quality in the region andare confined to the Leh district only. Despite lack of comprehensive information, this review aims to address three important questions: the hydrochemistry of water resources, the impact of urbanization on water quality, and the existing research gap in hydrochemistry in significant areas and water resources. The objective is to establish fundamental data for future research and contribute to a better understanding of water resources in the region.

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INTRODUCTION

According to the World Cities Report 2022 by the United Nations-Habitat [1], India's urban population is projected to reach 675 million by 2035, making it the second-largest urban population after China, which is expected to have one billion urban dwellers. The report highlights that urbanization is a prominent trend in the 21st century, with an estimated 43.2% of India's population residing in urban areas by 2035. The growth paths of major economies like China and India have a significant impact on global inequality, given their large population shares. While high-income nations differ in their urbanization rates and growth rates, the study emphasizes the crucial role of cities in shaping the future of humanity [1, 2]. As population growth, industrialization, urbanization, and economic development progress, water consumption and contamination of water bodies increase significantly. The paper notes that anthropogenic activities such as industrial and sewage waste contribute to severe pollution of water bodies [3].

Despite the crucial role of fresh water in supporting life, a significant portion of the Indian population consumes water that is contaminated. This has severe consequences, with over two million people dying due to polluted water. The

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degradation of drinking water quality is becoming increasingly evident in tourist destinations like Manali, a small town in Himachal Pradesh, as urbanization and tourism grow [4]. Similarly, South Asian countries are experiencing a decline in water quality due to unregulated urbanization, improper disposal of industrial and municipal waste, and inadequate filtration and disinfection practices. These factors contribute to the contamination of both surface and groundwater [5, 6]. Urbanization is not limited to lowland areas alone; it affects various regions, including mountainous areas such as Ladakh. The challenges faced in these areas include limited resources, difficulties in accessibility, and heightened vulnerability to population changes [7].

Anthropogenic activities in river basins have disrupted the self-purification capacity of rivers, leading to the degradation of this vital ecosystem. Surface water bodies are particularly susceptible to contamination due to the ease of discharging effluents into them [8]. This is especially true in arid and semi-arid regions where groundwater plays a crucial role in meeting drinking, residential, agricultural, and industrial needs. The contamination of groundwater by heavy metals poses a significant threat, even at low concentrations [9]. Climate change has both direct and indirect consequences on water resources, agriculture, and livelihoods, exacerbating the challenges. Increasing water demand from cities, businesses, and agriculture, along with rising pollution levels, seasonal water shortages, and floods, worsens the situation [10]. In areas such as Cameron Highlands, Malaysia, the water quality of rivers, including Bertam River, has been negatively impacted by the surge in construction, tourism-related activities, and farming [11]. Given the current trends of urbanization and tourism growth, it is imperative to adopt sustainable approaches to water supply to preserve the natural quality of water and ensure a sustainable future.

Ladakh, consisting of Leh and Kargil districts, became a separate union territory in India on October 31, 2019, following the Jammu and Kashmir Reorganisation Act, 2019. Since then, Leh district has experienced rapid urbanization due to the presence of administrative offices and a civilian airport. A study has highlighted the role of the army and tourism in the floating population as a significant factor contributing to urbanization in Ladakh [12, 13]. This shift from agriculture to a tourism-based economy in Leh has resulted in unequal access to water resources, causing detrimental social and environmental changes that have negatively impacted the quality and availability of water [14]. This urbanization trend in Ladakh bears similarities to a study conducted in China by Qian and co-workers [15], emphasizing the impact of tourism-driven urbanization. This study centers on the Leh Ladakh region of India, aiming to investigate various distinctive challenges such as rapid urbanization, the unique climate and water scarcity, the surge in tourism, and the transition from an agricultural to a tourism-based economy. These challenges are particularly unique to this region in contrast to other parts of the country. Additionally, the study seeks to offer insights into more sustainable water management practices and pollution control measures.

In the past, the residents of Ladakh used to build their homes on unsuitable soil used for farming, while utilizing areas with high groundwater levels for agriculture. However, there has been a significant shift in this trend recently. Agricultural and barren fields are now being converted into private housing or tourist infrastructure, erasing the distinction between cultivated and inhabited land. As a result, the reliance on traditional surface water systems for everyday use has been replaced by groundwater as the primary water source [14].

Despite the dearth of comprehensive data on the hydrochemistry of water resources in Leh, Ladakh, this review article endeavours to tackle several critical inquiries:

i. Explore Existing Research: Explorethe existing research conducted on hydrochemistry and related fields in the region, to provide a comprehensive understanding of the current state of knowledge.

ii. Assess Tourism-driven Urbanization Impact: Analyse the ramifications of tourism-driven urbanization on water quality in the region, shedding light on potential challenges and identifying areas for improvement.

iii. Anticipate Future Consequences: Forecast future consequences by drawing parallels with similar semi-arid areas where water quality issues are already prevalent, offering insights into potential trajectories and outcomes for Ladakh.

iv. Advocacy towards Sustainable Planning: Sensitize policymakers to the urgent need for sustainable future planning, emphasizing the importance of proactive measures to safeguard water resources and mitigate adverse effects of urbanization and tourism.

v. Identify Research Gaps: Identify and address research gaps in hydrochemistry pertaining to significant locations and water sources in Ladakh, facilitating targeted investigations and informed decision-making.

vi. Establish Baseline Data: Establish baseline data to serve as a foundation for future investigations into water quality and hydrochemistry in the region, enabling ongoing monitoring and assessment of environmental conditions.

By pursuing these objectives, this review aims to contribute to a deeper understanding of the hydrochemical dynamics in Leh, Ladakh, and suggest for sustainable practices to ensure the preservation and responsible management of water resources for future generations.

BRIEF ABOUT THE STUDY AREA

Ladakh, situated in the northernmost part of the trans-Himalaya region, is recognized as one of India's largest cold deserts. Its geographical coordinates lie between 31°44′57″ and 32°59′57″N latitude and 76°46′29″ and 78°41′34″E longitude (Fig. 1). The area falls under the rain shadow of the Greater Himalayas, shielding it from the influence of the southwest monsoon. Instead, it experiences the impact of

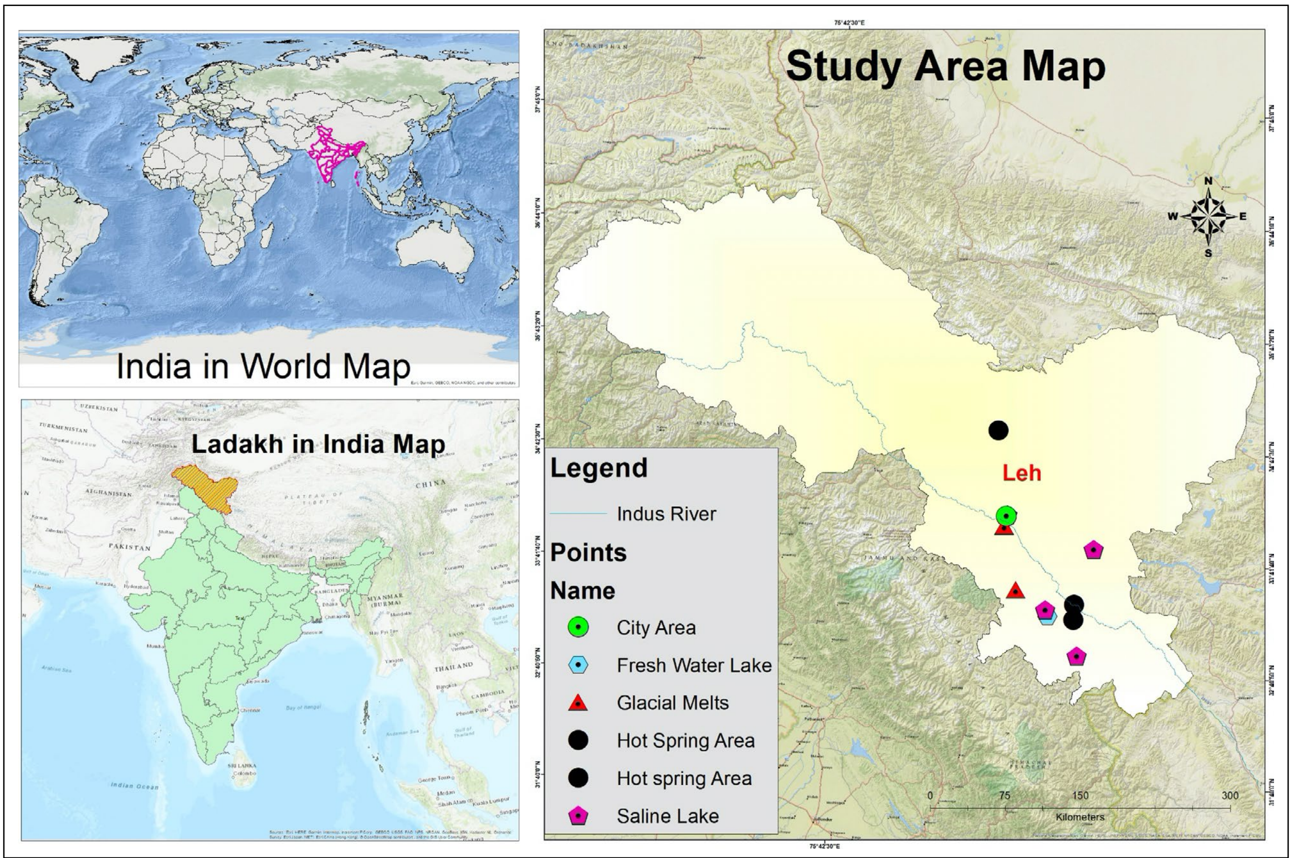


Figure 1. Study area map of Leh Ladakh region.

westerly winds [16, 17]. The region is characterized by extremely cold temperatures caused by the prevailing Arctic winds throughout most of the year, resulting in a distinctive climate characterized by extreme dryness. Ladakh receives low annual precipitation, with only 20–30 mm of rainfall or snowfall. It also has prolonged sub-zero temperatures, ranging from -30 °C to -75 °C in different areas. The terrain is rugged and challenging, and the humidity remains low, ranging from 20% to 40%. These conditions make Ladakh a semi-arid cold region [18, 19]. Despite these harsh conditions, Ladakh is rich in natural features such as high-altitude lakes, glaciers, streams originating from melting glaciers, barren mountains, steep gorges, hot springs, and rivers [18, 20]. The region's cultural diversity adds to its appeal, attracting trekkers, tourists, and researchers. The streams, rivers, springs, and groundwater, fed by glacial and snowmelt sources, are crucial sources of water for the population living in glacial-fluvial moraines, large scree deposits along foothills, and active mega alluvial fans within river valleys [21].

GEOLOGY OF LADAKH

The Ladakh Himalaya consists of five geotectonic units arranged in a north-to-south sequence [22]. These units are the Karakoram block, Shyok suture zone, Ladakh arc, Indus suture zone, and Tethys Himalayas (Fig. 2).The Karakoram block is a region characterized by a diverse range of rocks that span from the Late Precambrian to the Cretaceous period. Within this zone, there are metamorphic, igneous, and sedimentary rock types that were formed between the Permo-Carboniferous and Late Cretaceous periods. The metamorphic rocks found here consist of schists, quartzites, augen gneisses, and migmatites. The igneous rocks include granites, granodiorites, and tonalities, collectively known as the Karakoram Batholith. The sedimentary rocks present in this region encompass limestones, dolomites, shales, sandstones, as well as small occurrences of conglomerate lenses [23].

The Shyok suture zone, which separates the Ladakh arc from the Karakoram block, consists of mafic-ultramafic rocks, sedimentary rocks, and metamorphic rocks. Within the Shyok formation, there are two sections known as the lower and upper members. The lower member is primarily made up of sandstone, conglomerate, and some limestone, while the upper member is comprised of volcaniclastic rocks [22]. The Ladakh arc, which is part of the Trans-Himalayas, is a geological formation resulting from the movement of the Neo-Tethys oceanic plate beneath the Eurasian landmass. It comprises of batholithic, rhyolitic, and andesitic rocks. Spanning approximately 600 km in length and 30–80 km in width, the Ladakh arc is a substantial component of the Trans-Himalayas [24].

The Indus Suture Zone (ISZ) is a region where various geological units are juxtaposed from south to north. These units include the Lamayuru Complex, which is

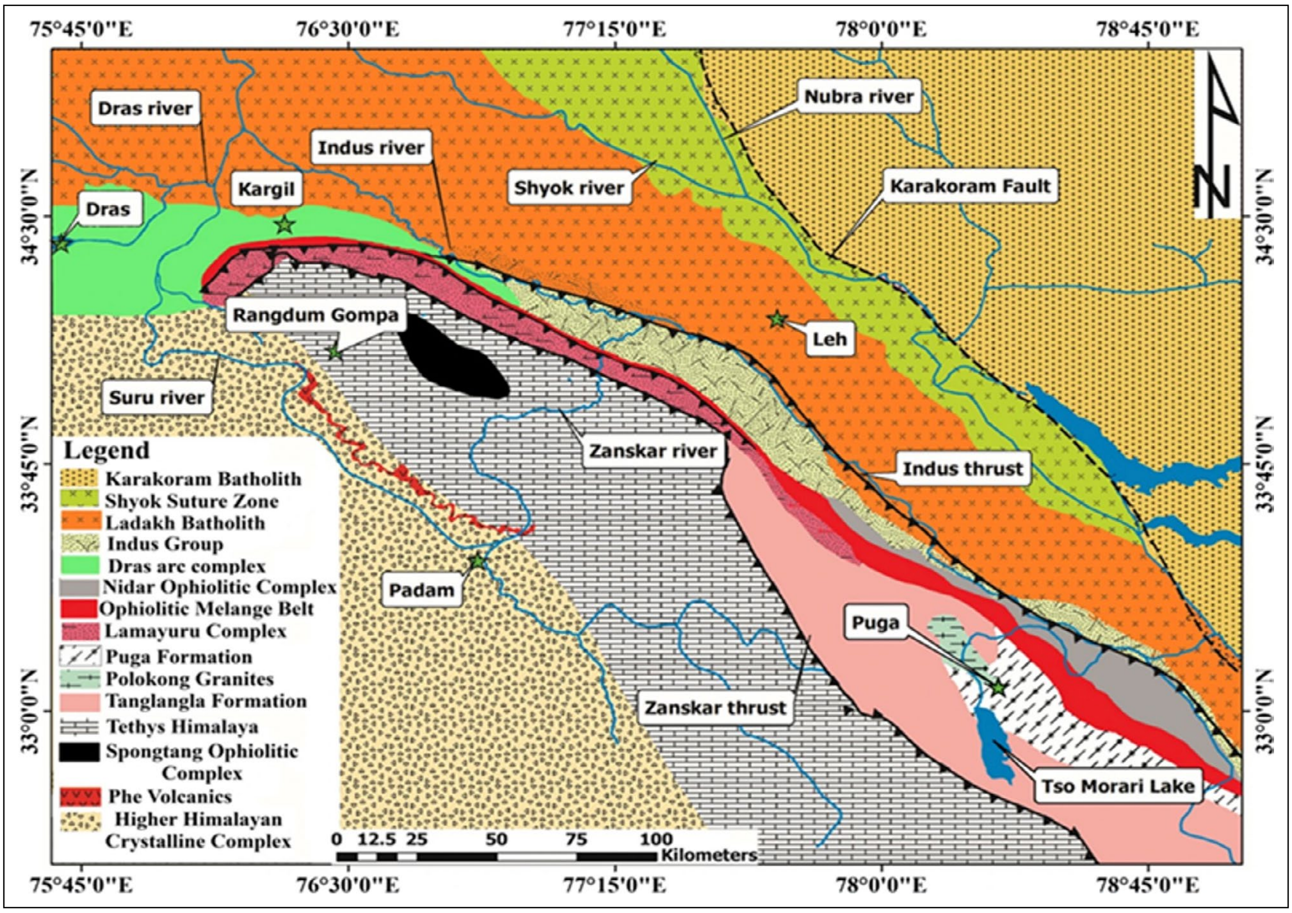


Figure 2. Geological map of the Ladakh Himalaya showing various tectonostratigraphic units. Reproduced with permission from Ref. [25], Copyright (2023) from Springer.

Note: The blue line (–––) Rivers and the black broken line (- - - -) signifies fault.

a deposit formed on a continental slope, an ophiolitic melange belt, the Dras arc complex representing an island arc formed within an ocean, remnants of the Neo-Tethys Ocean in the form of ophiolitic relics, the Indus Group consisting of molassic deposits, and the Ladakh Batholith, which is a plutonic complex. The age of these units spans from the Late Permian to the Eocene period [25].The Tethys Himalayas consist predominantly of fossil-rich sedimentary deposits that were formed between the Precambrian and Cretaceous periods along the northern edge of the Indian subcontinent. The northern section of this mountain range has undergone metamorphism at extremely high pressures [22].

HYDROCHEMISTRY OF WATER RESOURCES IN LADAKH

The Hindu Kush-Himalayan region is often referred to as the "Third Pole" due to its vast freshwater reserves, second only to the polar regions. These reserves exist in the form of glaciers, lakes, rivers, ponds, and springs, and are closely tied to the region's climate. The Ladakh region, an integral part of the Himalayas, relies primarily on precipitation, particularly snowfall in winter, as its main water source. As snow and ice melt during winter and early spring, they contribute to the sustained flow of perennial rivers downstream. These meltwaters, originating from glaciers and high-altitude snow, play a crucial role in the Indus River's flow, replenishing groundwater reserves, and nourishing alpine lakes [26].

Meltwater Chemistry

Glacier melts have traditionally been considered a clean source of water, but as temperatures rise, the interaction between water and rocks intensifies. This leads to the water becoming heavily contaminated with sediment and dissolved substances as it flows through channels within and beneath the glacier [27, 28]. The chemical composition of the water is also affected by various factors, such as the formation of basal ice layers during the winter, biological processes, cation exchange, mineral weathering, and ion separation during thawing and percolation through the snowpack [29, 30]. As a result, the meltwater becomes enriched with ions such as Ca^{2+}, Mg^{2+} and K^{+} compared to the original snow [30, 31]. Human activities associated with increased urbanization and tourism have further contributed to the deterioration of water quality in these areas [3].

The previous studies conducted in the area, as summarized in Table 1, indicate that the concentration of ions in glacial melts follows the order Ca^{2+} >> Mg^{2+} > Na^{+} > K^{+} and HCO_3^-

Table 1. Physicochemical parameters of glacial melts of Leh Ladakh

Source ID	Sampling period	pH	Na	K	Ca	Mg	HCO_3	SO_4	NO_3	Cl	TDS	F	Si	Ref
UG_GM_2010_EMP	Early melt period 2010	5.2–7.3	22.20–55.50	6.82–25.54	67.35–391	25.83–72.83	110–440	37.96–61.90	0.16–2.26	8.18–14.10				[30]
UG_GM_2010_EMP	Early melt period 2010	6.60	33.93	12.84	228.00	42.07	253.00	47.52	0.83	10.98				
UG_GM_2010_PMP	Peak melt period 2010	5.3–7.0	17.60–37.0	3.69–19.87	94.45–243	24.08–59.08	80–290	0.44–4.36	41.73–60.94	6.21–13.26				
UG_GM_2010_PMP	Peak melt period 2010	6.20	26.15	8.16	157.00	36.95	170.00	1.36	49.73	10.43				
UG_GM_2010_LMP	Late melt period 2010	6.4–7.2	33.40–127.10	9.69–14.97	190–1159	49.33–282	200–1450	0.09–2.68	41.25–62.27	0.65–1.45				
UG_GM_2010_LMP	Late melt period 2010	6.60	50.99	11.73	387.00	82.25	452.00	0.91	48.91	1.04				
LT_GM_2019_S	Summer 2019	7.30–8.30	34.0–81.0	0.56–1.17	6.64–24.86	0.95–3.28	18.30–42.70	3.91–16.54	1.37–2.36	0.13–1.72	32.4–91.95	0.06–0.13	0.38–0.76	[98]
LT_GM_2019_S	Summer 2019	7.83	54.20	0.72	11.88	1.73	31.11	5.38	1.73	0.51	57.29	0.72	0.56	
SK_GM_2019_S	Summer 2019	7.30–8.40	34.0–81.0	0.41–0.66	12.30–30.90	0.81–2.36	26.80–67.10	3.80–16.13	0.93–2.80	0.57–0.18	41.0–103.0	0.03–0.11	0.42–0.86	
SK_GM_2019_S	Summer 2019	7.96	72.30	0.52	24.27	1.47	53.92	10.15	1.70	0.39	94.90	0.06	0.62	
CN_GM_2019_S	Summer 2019	8.30–8.50	103.0–119.0	0.97–1.19	39.01–32.98	5.15–6.28	67.10–88.10	23.82–27.89	1.50–2.10	0.75–1.56	132.48–160.15	0.08–0.13	1.02–1.30	
CN_GM_2019_S	Summer 2019	8.36	112.40	1.08	31.11	5.81	73.74	26.70	1.72	1.00	145.00	0.10	0.11	
LT_GM_2018_S	Summer 2018	7.40–8.20	29.0–34.60	0.66–3.95	5.47–12.34	0.49–1.72	24.40–36.60	1.17–5.79	044–2.52	1.66–4.85	36.50–67.95	0.04–0.39	0.40–0.70	
LT_GM_2018_S	Summer 2018	7.77	47.27	2.16	9.60	1.39	31.52	4.11	1.28	2.71	54.85	0.16	0.53	
SK_GM_2018_S	Summer 2018	7.60–8.30	31.10–74.20	7.26–12.98	0.57–3.78	0.46–3.46	18.30–91.50	0.80–12.78	1.12–2.10	1.05–2.26	30.51–119.26	0.02–0.08	0.50–0.85	
SK_GM_2018_S	Summer 2018	7.95	52.33	11.35	2.05	2.04	66.49	5.53	1.47	1.62	93.46	0.05	0.73	
CN_GM_2018_S	Summer 2018	8.0–8.3	102.1–117.0	1.19–2.10	16.45–29.14	2.90–3.80	73.20–105.90	12.43–14.55	0.74–1.70	1.47–1.99	118.22–146.12	0.02–0.10	0.93–1.20	
CN_GM_2018_S	Summer 2018	8.13	108.15	1.75	20.31	3.20	85.23	13.23	1.33	1.74	129.75	0.08	1.05	

UG_GM: Upper Ganglass Glacial Melt; LT_GM: Lato Glacial Melt; SK_GM: Stok Glacial Melt; CN_GM: Chabe Nama Glacial Melt. S and W along with the years indicate sampling periods in summer and winter respectively. EMP, PMP, and LMP along with the years indicate sampling periods in the early, peak, and late melting periods respectively. The concentration of ions for the Upper Ganglass Catchment is in µeq/L, EC in µS/cm, and the remaining parameters are in mg/L.

>> SO_4^{2-} > Cl^- > NO_3^-> PO_4^-. This suggests that carbonate rock weathering plays a significant role in determining the chemistry of these melts. Additionally, the studies report a substantial contribution from calcite rocks, sulphide oxidation coupled with silicate weathering, ion exchange processes, and atmospheric deposition (such as alkaline dust, anthropogenic pollutants, and sea salt aerosol). These factors are further intensified by physical weathering in steep slopes [32].The high ratio of Ca^{+2}/Mg^{+2} (>4) and the dominance of Ca^{+2} over Na^+ also support the influence of carbonate rock weathering. Another study revealed that during the peak melt period, there is minimal residence time and interaction with the water surface, resulting in a relative decrease in solute content in the water [30].

River water (Indus)

The Himalayan glaciers play a crucial role as water reservoirs, supplying mountain rivers with water throughout the year [33–35]. In Ladakh, India, the Indus River is a significant source of drinking water and irrigation. Its origin lies in China, and it passes through Ladakh before reaching India [19, 36, 37]. Approximately 70% of the water in the Indus River comes from glaciers and heavy snowfall [19, 38, 39]. Previous studies, summarized in Table 2–4, indicate that the concentration of major ions in the Indus water basin generally follows the order, Ca^{2+} >> Mg^{2+} > Na^+ > K^+, HCO_3^- >> SO_4^{2-} >Cl^-. These studies also explain that Ca^{2+} and Mg^{2+} primarily result from the weathering of carbonate rocks, gypsum, or anhydrite, while Na^+ and K^+ originate from silicate rocks and numerous salt lakes present in the basin [19, 25, 26, 38–40]. Isotopic data and the $Ca^{2+} + Mg^{2+}/Na^+ + K^+$ ratio, which is almost three times the world average of 2.2, further confirm that weathering of carbonate lithology is the main factor influencing the chemistry of major ions. The concentration of silicate in the Indus water averages around 6 ppm, like other high-altitude rivers that drain from the Himalayas. However, in the lower-lying areas of the Indus, this value increases to 19 ppm, indicating a higher rate of chemical weathering in these regions compared to the highland areas where mechanical weathering is predominant. The Suru River, one of the tributaries of the Indus River, exhibits the highest reported rate of carbonate weathering due to its steep average catchment slope [19].

The information available in the literature highlights several key points about the composition and characteristics of the Indus River [19, 40–44].

i. Anions: The bicarbonate ions in the Indus River come from the weathering of carbonate rocks (~75%) and silicate rocks (~25%). The presence of SO_4^{2-} is attributed to the weathering of gypsum, while Cl^- originates from halite deposits.

ii. Weathering Processes: The weathering of gypsum by H_2SO_4 is explained by the higher concentration of SO_4^{2-} ions compared to Cl^- ions. Hot springs along the riverbank have high sulphur content which supports this weathering process. Additionally, the dissolution of at-

Table 2. Concentration of major ions (mg/L) in the Indus River, Leh Ladakh

Source ID	Sampling period	Value	Parameters												Ref
			HCO_3	Ca	Mg	Na	K	F	Cl	NO_3	SO_4	PO_4	CO_3	TOC	
IR_1991_S	Summar-1991	Range	78.6–104.3	20.9–24.2	4.6–5.5	3.4–13.3	1.0–1.6	0.1–0.3	1.8–8.6	0.9–9.3	12.3–29.0				[39]
IR_1991_S	Summar-1991	Mean	91.3	22.3	5	9.9	1.4		6.4	1.7	16.7				
IR_1996_S	Summar-1996	Range	67–107	18–28.8	1.5–7.1	5.6–9.4	1.7–1.9	0.12–0.57	3.3–7.3	0.10–0.17	9.2–21.4				[63]
IR_1996_S	Summar-1996	Mean	81.2	24	4.5	7.3	1.6	0.3	4.8	0.12	11.9				
IR_2009-10_S	Summar-2009-10	Range	14.04–30.60	61.68–73.81	29.28–33.86	60.19–62.53	30.20–31.42	0.02–0.47	12.81–27.63	0.02–0.09	0.36–4.84	0.09–1.94	0.00–6.88	0.40–7.30	[65]
IR_2009-10_S	Summar-2009-10	Mean	23.46	88.33	31.18	60.98	30.6	0.2	23.48	0.04	3.92	0.35	2.99	1.07	
IR_2009-10_W	Winter-2009-10	Range	11.84–28.40	63.76–84.62	29.69–35.90	60.56–64.66	30.54–33.18	0.2–0.7	10.32–28.23	0.1–3.4	2.00–6.48	0.01–1.86	0.19–6.43	0.25–7.15	
IR_2009-10_W	Winter-2009-10	Mean	21.26	66.99	31.49	62.16	31.63	0.4	20.44	1.5	2.28	0.27	2.55	0.92	
IR_2011_S	Summar-2011	Range	82.2–140.6	17.0–38.1	4.9–7.7	2.7–14.5	1.1–2.0		1.4–10.1	0.0–0.2	12.7–32.9				[99]
IR_2011_S	Summar-2011	Mean	107.1	27.3	6.2	8.1	1.5		4.6	0.1	21.7				
IR_2013_S	Winter-2013	Range		31.09–52.99	5.05–6.3	10.81–79.53	0.3–114.3	0.31–0.20	16.1–30.0	1.34–0.45	43.7–72.30	ND			[97]
IR_2013_W	Winter-2013	Mean		41.66	5.78	50.3	62.6	0.24	24.9	0.86	57.7				
IR_2019_S	Summar-2019	Range	97.60–80.60	32.27–26.50	7.61–6.64	15.87–10.56	2.59–1.87	0.26–0.11	6.82–4.22	0.89–0.58	27.34–21.45				[98]
IR_2019_S	Summar-2019	Mean	87.17	27.86	7.07	13.73	2.1	0.21	5.34	0.8	23.39				
IR_2018_S	Summar-2018	Range	118.0–107.0	23.0–19.0	5.60–4.30	6.55–2.30	2.50–1.90		7.01–3.26	1	24.0–18.47				
IR_2018_S	Summar-2018	Mean	110.93	21.4	4.95	5.29	2.13		6.11		20.2				
GM*		Mean	58.4	15	4.1	2.3	6.3		7.8		11.2				[61, 99]

*Global Mean of Some Major Rivers of the World. IR: Indus River: S and W along with the years indicates sampling period in summer and winter, respectively; ND: Not detected.

Table 3. Physicochemical and biological parameters of Indus River, in Leh Ladakh

Source ID	Parameters													Ref
	DO (mg/L)	Free CO_2 (mg/L)	Alkalinity (mg/L)	Hardness (mg/L)	pH	Conductivity (μScm^{-1})	T (^0C)	TDS (mg/L)	Salinity (mg/L)	Turbidity (mg/L)	COD (mg/L)	*E. coli* (CFU/mL)	TOC (mg/L)	
IR_1996_S					8.1–8.5	112–187		100–260						[63]
IR_1996_S					8	116.3	15.7							
IR_2009-10_S	7.15–11.71		226.00–406.00	53.00–245	8.15–8.53	303.00–476.00	12.20–19.70	145.90–176.20	0.10–0.20	0.60–11.22		2.00–98.00	0.40–7.30	[65]
IR_2009-10_S	10.17		333.43	187.27	8.36	336.43	15.66	155.41	0.11	4.97		8.18	1.07	
IR_2009-10_W	10.00–11.46		108.00–524.00	51.56–206.92	7.56–8.72	0.23–130.00	14.88	0.24–156.00	0.00–0.30	0.87–7.22		0.00–77.00	0.25–7.15	
IR_2009-10_W	10.69		319.25	150.67	8.33	326.65	15.20–16.40	103.46	0.1	3.38		6.48	0.92	
IR_2009_10_S					7.58	243.78		121.51	0.12	1.17	31.45			[59]
IR_2011_S					7.4–8.0	232.0–316.0		150.1–223.1						[64]
IR_2011_S					7.7	260.1		184						
IR_2013_S	10.2–14.2	14.9–13.2	263.5-282.0	144–192										[97]
IR_2013_W	11.65	14.1	272.1	158										
IR_2019_S					8.50–7.70	153–132		179.27–161.34						[98]
IR_2019_S					8.35	138		169.62						
IR_2018_S					7.80–8.32	155–140		181.85–164.57						
IR_2018_S					8.13	147.67		173.89						
GM*					8			120						[61, 64]

*Global Mean of Some Major Rivers of the World. IR: Indus River: S and W along with the years indicates sampling period in summer and winter, respectively.

Table 4. Concentration of heavy metals and other parameters in the Indus River, in Leh Ladakh

Source ID	Value	Parameters																Ref
		SiO_2 (mg/L)	U-238 (µg/L)	$^{234}U/^{238}U$	Rb (nmol/L)	Sr (nmol/L)	$^{87}Sr/^{86}Sr$	Ba (µg/L)	Fe (mg/L)	Mn (mg/L)	Zn (mg/L)	Si (mg/L)	Al (mg/L)	As (mg/L)	Cd (mg/L)	Pb (mg/L)	Cr (mg/L)	Ni (mg/L)	
IR_1991_S	Range		1.57–4.94	1.09–1.22	10–77	1396–3689	0.7104–0.7116												[39]
IR_1991_S	Mean		3.12	1.2	46.3	2175.5	0.7111												
IR_1996_S	Range	2.8–9.8																	[19]
IR_1996_S	Mean	6.2				113ppb	0.7104	15.7	27.8 ppb	<10 ppb	15.6								
IR_2009-10_S	Range								1.02–1.13	0.87–1.67									[65]
IR_2009-10_S	Mean								1.06	1.23									
IR_2009-10_W	Range								1.04–1.13	0.34–1.00									
IR_2009-10_W	Mean								1.07	0.62									
IR_2009_10_S	Range													0.001–0.099	0.012–0.036	0.043–0.275	0.019–0.275	0.001–0.062	[59]
IR_2009_10_S	Mean													0.075	0.024	0.111	0.024	0.016	
IR_2013_S	Range								0.3-1.4	0.146–0.177		27.2–92.57	0.002–1.88						[97]
IR_2013_W	Mean								0.6			62.47	0.842						
IR_2019_S	Range	2.12–1.65																	[100]
IR_2019_S	Mean	1.86																	
*GM		7.63																	

*Global Mean of Some Major Rivers of the World. IR: Indus River; S and W along with the years indicates sampling period in summer and winter, respectively.

mospheric CO_2 increases the concentration of carbonic acid in the water, accelerating chemical rock weathering along with H_2SO_4. Low pCO_2 values support the coupling of carbonate dissolution and sulphide oxidation, while C-ratio values between 0.75 and 0.9 indicate the protonation of meltwater due to the dissociation and dissolution of atmospheric CO_2. C-ratio values above 0.5 indicate that rapid calcite weathering is predominant over sulphide oxidation.

iii. Carbonate Hydrolysis: The low concentration or absence of CO_3^{2-} ions suggests hydrolysis of CO_3^{2-} to HCO_3^-. The dissolution of atmospheric CO2 further enhances the concentration of bicarbonate ions through CO_2 dissolution.

iv. Anionic Load: Studies indicate that the Indus River carries a higher anionic load compared to other Himalayan rivers. This is attributed to the dominance of carbonate minerals over silicate minerals, as shown by strong correlations between various ions such as Ca^{2+}- HCO_3^-, Mg^{2+}-HCO_3^-, Ca^{2+}-Mg^{2+}, Na^+- HCO_3^-, and Mg^{2+}-Na^+.

v. Nitrate (NO_3^-) Levels: NO_3^- concentrations in the Indus River range from <1 to ~3 ppm, which is relatively low compared to global averages and other neighbouring rivers. This suggests a minimal impact from anthropogenic and agricultural activities. However, reports indicate that nitrate levels can reach up to 25.6 ppm in streams near villages due to the use of fertilizers in agricultural activities. Therefore, caution should be exercised regarding drinking water from such areas.

vi. Microplastics: A research project found microplastic concentrations ranging from 60 to 340 MP/Kg DW (microplastic particles per kilogram of dry weight) in the Indus River. Despite having fewer people living along the Indus River in Ladakh compared to the Brahmaputra River in Assam, Arunachal, and Bangladesh, the microplastic levels were found to be comparable between the two rivers.

Overall, these findings provide insights into the chemical composition and environmental challenges faced by the Indus River, including the impact of weathering processes, carbonate hydrolysis, anionic load, nitrate pollution, and microplastic contamination.

Groundwater

According to a stable isotopic study conducted, the primary sources of groundwater recharge in Leh town are glacial and snow melts, contributing 44% and 39%, respectively [26, 45]. In contrast, rainfall has a lesser contribution of approximately 17% to groundwater recharge. Studies on various physicochemical parameters of groundwater in Leh town indicate that the dominant ionic species in the samples were Ca^{2+} and HCO_3^{2-}, suggesting carbonate weathering (Tables 5–7). Most of the samples belong to the Ca^{2+}-Mg^{2+}-HCO_3^- type, while the remaining samples follow the Ca^{2+}-Mg^{2+}-Cl^-- SO_4^{2-} composition [13, 20, 46].

Table 5. Concentration of major ions (mg/L) in the ground water, in Leh Ladakh

Source ID	Sampling period	Value	Parameters										Ref
			HCO_3	Ca	Mg	Na	K	F	Cl	NO_3	SO_4	PO_4	
HS1_1996_S	Summar-1996	Mean	94	27.4	1.1	300	22	6.7	90	0.3	225		[63]
HS2_1996_S	Summar-1996	Mean	939	13.8	1.6	610	80	17	425	0.6	115		
HS2_2011_W	Winter-2011	Mean	817.5	8.3	8.7	330.9	59.1	11.1	384.9	1.86	663.5		[47]
HS3_2011_W	Winter-2011	Mean	600.3	0.2	3.9	320.2	44.6	14.1	86.4	0.93	117.6		
HS4_2011_W	Winter-2011	Mean	275.8	7.2	7.3	101.3	9.1	5.7	6.5	1.05	40.9		
HS5_2011_W	Winter-2011	Mean	263.6	1.9	3.9	120.7	6.9	9.0	6.2	2.48	61.6		
HS6_2011_W	Winter-2011	Mean	207.4	1.1	4.1	80.2	5.04	11.8	9.0	0	46.7		
HS1_2011_W	Winter-2011	Mean	447.8	3.9	2.9	320.1	55.6	10.1	333.8	1.7	657.5		
GW_2013_S	Summar-2013	Range		11.77–45.11	2.92–26.35	0.1–31.9	0.8-3.2		2.13–4.97		9.39–13.70	0–0.47	[13]
GW_2013_S	Summar-2013	Mean		32.15	14.04	7.54	1.6		3.51		10.69	0.06	
GW_2013_W	Winter 2013	Range		47.03–107.40		4.87–45.41	1.01–97.71		12.53–27.42	0.0–0.2	11.53–83.41		[97]
GW_2013_W	Winter 2013	Mean		76.61			20.13		18.8	0.1	42.9		
GW_2015_S	Summar-2015	Range	9.48–54.50	25–123	14.26–68.43	100–420	10.05–36.88		10.81–39.24		0.21–0.71	0.01–0.17	[38]
GW_2015_S	Summar-2015	Mean	28.23	60.92	40.75	234.5	24.76		22.74		0.46	0.04	

HS: Hot springs; GW: Ground water; HS1: Chummathang; HS2: Puga hotspring; HS3: Changlung; HS4: Pulthang; HS5: Panamic; HS6: Gaik. S and W along with the years indicates sampling period in summer and winter, respectively.

Table 6. Physicochemical parameters of ground and lake water, Leh Ladakh

Source ID	Value	Parameters								Ref
		DO (mg/L)	Free CO_2 (mg/L)	Alkalinity (mg/L)	Hardness (mg/L)	pH	Conductivity (μS/cm)	T (^{0}C)	TDS (mg/L)	
FW2_1996_S	Range					8.5–8.7	84–93	13.2–13.4		[39]
FW2_1996_S	Mean					8.6	88.5	13.9		
SL3_1932	Mean	7.4		255		9				[17]
SL3_2000	Mean	4.5		575		8	1058			
SL3	Range					8.9–9.02	3360–3740		2150–2393	[51]
SL4	Mean				3160	8.96	3550		2272	
SL5	Range				18292–21195	8.8–8.84	62720–64340		40141–41178	[96]
SL5	Mean				19743	8.82	63530		40659	
HS1_1996_S	Mean					7.5	1735			[63]
HS2_1996_S	Mean					8	3100			
HS2_2011_W	Mean					8	2790	84	1953	[100]
HS3_2011_W	Mean					7	2650	74	1855	
GW_2013_S	Range				90–188	7–8	205–849		134–565	[13]
GW_2013_S	Mean				135	7.55	441.51		291.22	
GW_2013_W	Range	5.9–9.6	11.6–19.2	160–310	140–300					[97]
GW_2013_W	Mean	7.9	16.1	257.4	220.1					
GW_2015_S	Range	9.27–10.65		202–696	81.25–837.11	7.13–8.58	139–1143	14.90–1960	66.40–563.0	[38]
GW_2015_S	Mean	10.03		494.49	235.99	7.7	488.74	17.24	238.5	

HS: Hot springs; GW: Ground water; HS1: Chummathang; HS2: Puga hotspring; HS3: Changlung; FW1: Chakratal Tso; FW2: Startspuk Tso; SL1: Pangong lake; SL2: Kiagar Tso; SL3: Tso morari; SL4: Tsokhar; SL5: Tsokhar Lake; S and W along with the years indicates sampling period in summer and winter, respectively.

Hot Springs

Ladakh is famous for its hot springs, which can be found in various locations such as Changlung, Pulthang, and Panamic in the Nubra Valley, Gaik and Chumathang in the Indus Valley, and Puga in the Puga Valley. These hot springs have temperatures ranging from 83 to 107°C, with Chumathang and Changlung being the hottest and Gaik being the coolest [47]. While temperatures exceeding 250 °C are expected at greater depths (3 km), studies using silica and cation geothermometry indicate that temperatures at shallower depths are around 150 and 250 °C [48].

To gain insights into the potential sources of recharge for the geothermal system's aquifer zone, stable isotopes of oxygen (^{18}O) and hydrogen (D) in the geothermal water can be analyzed. An isotopic analysis revealed that precipitation and groundwater are the primary sources of recharge for most hot springs [49]. However, in the cases of Puga and Chumathang, the isotopic composition suggests that their recharge may come from deeper sources, possibly associated with magmatic activity. This is supported by the elevated levels of trace elements, such as arsenic (As), which indicate mixing with high-temperature fluids from deeper regions.Reported studies on various physicochemical parameters of hot springs in Leh town are summarized in Tables 5–7. The major anions found in geothermal waters are HCO_3^-, Cl-, and SO_4^{2-}, while the major cations are Na^+ and K^+. In nonthermal waters, the composition is reversed. The concentrations of dissolved salts in thermal waters are mainly controlled by the processes of silicate weathering and ion-exchange kinetics. The presence of minerals like thenardite, pyrite, and jarosite in the basement rock encountered by high-temperature fluids leads to enrichment of Cl^- and SO_4^{2-} ions in the geothermal waters [47–49]. Considerable amounts of trace elements such as iron (Fe), boron (B), lithium (Li), strontium (Sr), manganese (Mn), aluminium (Al), molybdenum (Mo), zinc (Zn), and arsenic (As) have also been reported, indicating possible interaction between the geothermal waters and the surrounding rocks [47].

Two types of hot springs have been identified in Ladakh: periphery types, found in Changlung, Pulthang, Panamic, and Gaik, which demonstrate evidence of subsurface mixing of deep fluids with meteoric water; and volcanic types, found in Chumathang and Puga, characterized by their volcanic origin at the surface.The geothermal fields of Ladakh have the capacity to release approximately 2.9×10^7 moles/year of CO_2 into the atmosphere, with Changlung, Pulthang, and Panamic contributing 2.9×10^6 moles/year from the Nubra Valley, and Puga, Chumathang, and Gaik contributing 2.05×10^7 moles per year from the Indus and Puga valleys region [47]. According to the "Geothermal Atlas of India" published by the Geological Survey of India (GSI) in 1991, Panamik in the Nubra Valley and Chamuthang and Puga in the Indus Valley have the potential for geothermal power generation ranging from 3 to over 20 megawatts (MW) electricity. The concentrations of iron (Fe) and aluminium (Al) in the Ladakh region's geothermal waters vary from 5 to 118 µg/L, while boron (B) is a major ion in the geothermal waters of Puga and Chumathang, with concentrations ranging from 444 to 30194 µE [18].

Table 7. Heavy metal concentrations in ground and lake water, Leh Ladakh

Source ID	Value	Parameters											Ref
		SiO_2 (mg/L)	Rb (nmol/L)	Sr (nmol/L)	$^{87}Sr/^{86}Sr$	Ba (µg/L)	Fe (mg/L)	Mn (mg/L)	Zn (mg/L)	Si (mg/L)	Al (mg/L)	As (mg/L)	
FW1_1991_S	Mean		38	1298	0.7093								[39]
FW2_1991_S	Mean		13	1340	0.7238								
FW2_1996_S	Range	0.3–1											[63]
FW2_1996_S	Mean	0.6		60		9	ND	ND	<10				
SL1_1991_S	Mean		521	1192	0.7102								[39]
SL2_1991_S	Mean		926	81	0.7302								
SL3_1991_S	Mean		46	605	0.7168								
SL4_1991_S	Mean		4056	625	0.7198								
SL3_2000	Mean			0.002 ppm									[17]
HS1_1996_S	Mean	114		336		36 ppm		<10	<10				[63]
HS2_1996_S	Mean	190		294			80	92	2		33	181	
HS2_2011_W	Mean	3660											[100]
HS3_2011_W	Mean	3733											
GW_2013_W	Range						0.07–3.463	0.146–0.919		11.69–279.0	0.016–2.838		[97]
GW_2013_W	Mean						0.95	0.19		63.2	1.62		
GW_2015_S	Range						1.01–5.01	0.01–0.99	0.07–3.67				[38]
GW_2015_S	Mean						1.95	0.61	0.89				

HS: Hot springs; GW: Ground water; HS1: Chummathang; HS2: Puga hotspring; HS3: Changlung; FW1: Chakratal Tso; FW2: Startspuk Tso; SL1: Pangong lake; SL2: Kiagar Tso; SL3: Tso Morari; SL4: Tsokhar; SL5: Tsokhar Lake; S and W along with the years indicates sampling period in summer and winter, respectively.

Lake Water

The literature review conducted on lakes in Ladakh highlights the presence of two types of lakes, namely fresh and saline (brackish) lakes. The composition of these lakes varies significantly based on the geographical characteristics of the area and the level of evaporation they have undergone. The lakes like Tsomoriri and Tsokar exhibit high salinity resulting in exceptionally high salinity and conductivity due to the absence of drainage rivers leading to the ocean, which allows salts and minerals to accumulate from the surrounding mountains. This phenomenon is primarily attributed to the prevailing cold desert climate, and high evaporation rates, characterized by low annual rainfall of approximately 100 mm [19, 50–52]. The suitability of these lakes for various purposes, as well as their physical and chemical parameters, are summarizedin Tables 6–9.

ASSESSMENT OF HYDROCHEMICAL PARAMETERS OF THE LADAKH REGION

pH

pH is a crucial parameter for assessing water quality as it reveals important information about the chemical equilibrium and solubility of various substances in water. The pH value of water is typically 7, indicating neutrality. Any deviation above or below 7 suggests natural or human-induced changes in the water chemistry [53, 54]. The previous studies reveal that pH ranges of all water resources fall between 7.1 and 9.0, indicating that they are slightly alkaline in nature. However, apart from saline lakes, all these water sources are within the acceptable limits recommended by World Health Organization (WHO) and BIS, which is between 7 and 8.5 (Tables 1, 3, and 6).

Electrical Conductivity

Conductivity is an important parameter that indicates the concentration of dissolved ions, or the amount of soluble salts, in a body of water. Significant changes in conductivity can suggest the presence of discharge or contamination in the aquatic environment [54]. As evident from the data presented in Tables 1, 3, and 6, the conductivity levels ranged from 88.5 to 63530 (µS/cm), with higher values in saline lakes resulting from the dissolution of ionic species from the surrounding rocks. The WHO sets a standard that the electrical conductivity value should not exceed 400 µS/cm [55]. Previous reports indicate that all water sources, except for hot springs and saline lakes, are within the permissible limit [53]. A study conducted in 2000, measured the electrical conductivity of Tsomorari lake as 1058 µS/cm [17]. However, subsequent studies have shown values exceeding the permissible limit, indicating an increase in the dissolution of ionic compounds and evaporation. The classification of water quality based on electrical conductivity is shown in Appendix 1 [53].

Total Dissolved Solids (TDS)

Water has a natural ability to dissolve various minerals and salts, both organic and inorganic. This includes while

Table 8. Concentration of major ions (mg/L) in the lake water, Leh Ladakh

Source ID	Sampling period	Value	Parameters										Ref
			HCO_3	Ca	Mg	Na	K	F	Cl	NO_3	SO_4	PO_4	
FW1_1991_S	Summar-1991	Mean		26.2	7	12.6	3.9		12.1		36		[39]
FW2_1991_S	Summar-1991	Mean		18.3	10.1	20.5	4.7		17.6		20.3		
FW2_1996_S	Summar-1996	Range	53.6–60.3	16.6–20.1	2.8–3.3	1.4–3.3	1.7–2.1	0.2	0.8–2.6	0.2–1.2	2.8–3.5		[63]
FW2_1996_S	Summar-1996	Mean	56.95	18.2	3.1	2	1.9	0.2	3.2	0.6	3.2		
SL1_1991_S	Summar-1991	Mean		3440	0.4	2.9	0.2		0.3		0.3		[39]
SL2_1991_S	Summar-1991	Mean		1400	0.2	1.4	0.3		0.3		2.4		
SL3_1991_S	Summar-1991	Mean		12000	0.2	1.4	17940		21655		0.4		
SL4_1991_S	Summar-1991	Mean		99200	19.6	46	14.2		60.9		80.1	0.02	
SL3_1932	1932	Mean	599	13	182	89	56		22		517		[17]
SL3_2000	2000	Mean	325	25.4	332.4	102.9	3.45	0.849	34.4	0.427	493.1		
SL3	NA	Range	0–2	30–40	744–750	89–1493	98–319	0.44–0.50	24		32–144	0.03–0.04	[51]
SL4	NA	mean	1	35	747	791	209	0.47	24		88	0.04	
SL5	NA	Range	2–6	760–1840	3330–4690	628–1493	1470–1960	0.42–0.60	8850–9206		16–36	0.16–0.43	[96]
SL5	NA	Mean	4	1300	4010	1061	1715	0.51	9028		26	0.3	

FW1: Chakratal Tso; FW2: Startspuk Tso; SL1: Pangong Lake; SL2: Kiagar Tso; SL3: Tso Morari; SL4: Tsokhar; SL5: Tsokhar Lake; NA: Data not available; S and W along with the years indicates sampling period in summer and winter, respectively.

Table 9. Suitability of different water sources based on residual sodium carbonate (RSC), magnesium hazard (MH), percent sodium (%Na), sodium adsorption ratio (SAR) and corrosivity ratio (CR) [101]

Source ID	TH	RSC	MH	%Na	SAR	CR	Remarks
IR_1991_S	76.8	0.8	18.3	29.3	0.7	0.6	Most of the water from Indus River, Glacial Melts and Groundwater are soft, <0 RSC level, Low MH, <60 %Na level, falls under C1S1 & C1S2 categories (SAR) and low CR make the water quality good to excellent for agriculture and can be transported through iron pipes.
IR_1996_S	78.9	0.6	15.8	23.8	0.5	0.5	
IR_2009-10_S	351.8	-3.1	26.1	43.4	2.0	2.8	
IR_2009-10_W	299.7	-2.6	32.0	48.8	2.2	2.7	
IR_2011_S	94.3	0.8	18.5	22.3	0.5	0.5	
IR_2013_W	128.4	-1.3	12.2	70.4	2.7	NA	
IR_2019_S	99.3	0.5	20.2	31.2	0.8	0.7	
IR_2018_S	74.3	1.1	18.8	22.0	0.4	0.5	
FW1_1991_S	94.9	-0.9	21.1	33.2	0.8	NA	
FW2_1991_S	88.2	-0.9	35.6	47.0	1.3	NA	
FW2_1996_S	58.5	0.4	14.6	15.5	0.2	0.3	
GW_2013_S	139.3	-1.4	30.4	16.5	0.4	NA	
GW_2013_W	191.5	-1.9	0.0	20.8	0.0	NA	
GW_2015_S	323.5	-2.8	40.1	71.8	8.0	2.3	
UG_GM_2010_EMP	746.7	-3.2	15.6	11.0	0.5	0.5	
UG_GM_2010_PMP	547.7	-2.6	19.1	12.5	0.5	0.2	
UG_GM_2010_LMP	1313.0	-5.6	17.5	8.6	0.5	0.0	
LT_GM_2019_S	37.0	0.1	12.7	8.7	0.1	0.4	
SK_GM_2019_S	66.8	0.2	5.7	8.3	0.1	0.4	
CN_GM_2019_S	102.2	0.2	15.7	9.0	0.2	0.8	
LT_GM_2018_S	29.8	0.2	12.6	24.4	0.2	0.5	
SK_GM_2018_S	13.7	1.0	49.9	76.7	0.4	0.2	
CN_GM_2018_S	64.2	0.8	13.6	13.3	0.1	0.4	
SL1_1991_S	8601.7	-86.0	0.0	0.1	0.0	NA	Saline water lakes are hard to very hard range, <0 RSC level, high MH, >40 %Na level, falls under C3S1 categories (SAR) and high CR value make the water quality unsuitable for agriculture as well as transportation through iron pipes.
SL2_1991_S	3500.8	-35.0	0.0	0.1	0.0	NA	
SL3_1991_S	30000.8	-300.0	0.0	59.9	0.0	NA	
SL4_1991_S	248082.3	-480.8	0.0	0.1	0.1	NA	
SL3_1932	796.9	2.1	93.3	42.6	1.9	1.9	
SL3_2000	1459.6	-9.1	92.9	22.9	1.7	3.5	
SL4	3224.9	-32.0	95.5	56.1	8.6	251.9	
SL5	20092.0	-199.5	75.5	34.3	4.6	6462.1	
HS1_1996_S	73.1	0.8	3.9	91.9	21.6	7.7	The parameters TH, RSC, MH, % Na, SAR and CR levels for the hot springs are above the desired level for agricultural purposes. Hence, highly unsuitable for agriculture and transportation through iron pipes.
HS2_1996_S	41.2	15.2	10.4	97.8	58.5	1.5	
HS2_2011_W	57.2	13.1	51.4	95.8	27.0	3.0	
HS3_2011_W	17.0	9.8	94.2	98.9	47.9	0.8	
HS4_2011_W	48.7	4.1	50.4	88.4	9.0	0.4	
HS5_2011_W	21.0	4.2	67.6	95.7	16.2	0.6	
HS6_2011_W	20.1	3.3	79.7	94.2	11.0	0.6	
HS1_2011_W	21.7	7.2	42.5	98.2	42.4	5.2	

the major cations are Na^+, K^+, Ca^{2+}, Mg^{2+}, HCO_3^-, Cl^-, and SO_4^{2-} ions and many others. When these minerals and salts dissolve in water, they can impart an unpleasant taste and colour to it. The concentration of dissolved ions in water is reflected by the measurement of total dissolved solids (TDS). Higher TDS values indicate a greater concentration of dissolved ions in water. When using water, TDS is an important parameter to consider. For drinking purposes, it is desirable for water to have a TDS limit of 500 mg/L, with a maximum allowable limit of 2000 mg/L. The TDS values for different water sources mentioned in Tables 1, 3 and 6 fall within the desirable TDS limit, except for the waters found in saline lakes and hot springs.The classification of water quality based on TDS is described in Appendix 2 [53].

Total Hardness

Chemical weathering of rocks has a significant impact on the chemical composition of water sources in Ladakh, particularly in relation to the presence of Ca^{2+}, Mg^{2+}, CO_3^{2-}, HCO_3^-, Cl^-, and SO_4^{2-} ions, which are responsible for determining the total hardness (TH) of the water. While calcium carbonate is used as a representation of total hardness, other chemical components also contribute to this measurement. The levels of ions that contribute towards hardness of water indicate that the primary source is the chemical weathering of rocks. According to the standards set by the Bureau of Indian Standards (BIS), the acceptable and permissible limits for total hardness in drinking water are 200 ppm and 600 ppm, respectively. Based on this criterion, all the water sources fell within the permissible limit, except for the water from saline and hot springs [53].The classification of water quality based on total hardness is shown in Appendix 3.

Heavy Metals

Heavy metals pose a significant threat to humans and other organisms as they are highly carcinogenic and can cause various diseases. A study conducted on groundwater in Leh city found significant pollution due to the accumulation of Cr, Cd, Ni, Mn, Fe and Cu (Table 7) [56]. The contamination was worsened using pesticides, agricultural chemicals, and soak pit effluents. A study in the Upper Indus River Basin of Ladakh by Lone et al. [57] found that arsenic levels in groundwater varied from 1.1 to 86 μg/L, with an average of 22 μg/L. Approximately 70% of analysed water samples had arsenic concentrations above 10 μg/L above the WHO limit for drinking water. Arsenic levels increased with rising water temperature and well depth, indicating a positive correlation between arsenic and temperature, suggesting that higher temperatures facilitate arsenic release [24]. The increase in tourism and urbanization in the region has led to a surge in groundwater extraction. As groundwater extraction intensifies, water levels decrease, prompting people to extract water from deeper depths, thereby increasing the risk of arsenic contamination in groundwater. Arsenic (As) concentrations were found to be higher in hot springs than in local groundwater, with volcanic and ophiolitic melange aquifers being identified as primary sources of the metal. It was recommended to paint the wells red as arsenic is poisonous and carcinogenic, posing a risk to millions of people. High-temperature thermal water exhibited better reactivity and higher metal concentrations, possibly due to leaching from the host rock [58]. Fe and Al concentrations varied from 5 to 118 μg/L in the Ladakh region, while boron concentrations in geothermal waters of Puga and Chumathang ranged from 444 to 30194 μE. Arsenic (As) concentrations were also high in geothermal springs, indicating a magmatic source for these fluids [47]. Heavy metal concentrations in Ladakh, except in hot springs and saline water lakes, were within permissible limits. However, a sensitivity analysis conducted on groundwater revealed that factors such as body weight, exposure length, and metal content were the main determinants of overall health risks. Another study found concentrations of heavy metals such as Cd, As, and Pb above the WHO's permissible limit in the Indus River, irrigation water, and stagnant water at various locations in Leh [59].

Other Chemical Species

The higher levels of Cl^- and SO_4^{2-} ions in the Indus River can be attributed to factors such as the dissolution of evaporates, the burning of sulfur-containing fossil fuels, and the contribution from biological sources through atmospheric transport [40, 60]. However, it has been reported (Table 2) that the concentration of NO_3^- ions in the Indus River is relatively low compared to the global average (1 mg/L) and other nearby rivers. The values fall below the permissible limit set by the Environmental Protection Agency (EPA) of 10 mg/L. This indicates a minimal impact from human activities and agriculture, and thus there is no significant concern for human health [40, 61].

According to a report, higher levels of Mg, Na, K, Mn, Ca, Cl, S and Al were found in the Indus River water collected near the city area of Leh [62]. This suggests an impact of human activities on the water sources in that area. Additionally, the concentrations of Al and alkalinity exceeded the limits prescribed by the WHO. However, few other studies have indicated that the water chemistry in the Indus River is primarily influenced by the surrounding geology (lithology) and not by human activities [39, 63, 64]. They found no evidence of anthropogenic influences on the water chemistry and concluded that most surface water in the region is suitable for drinking, except for salt lakes and hot springs. These studies did note that the TDS concentration was moderate compared to other major rivers in the Himalayan region, such as the Ganges and Brahmaputra. Another study reported that anthropogenic activities and agricultural waste are the main factors affecting the water quality of the Indus River [65].They found that these effects are more prominent during the summer season, indicating the impact of tourism on water quality.

HYDROCHEMICAL FACIES IN DIFFERENT SOURCES

Piper Diagram

The Piper trilinear diagram, developed by Piper in 1944, is a graphical representation used to analyse and compare the chemical composition of water samples. It displays the relative concentrations of different ions present in the water, allowing for the identification of specific chemical facies or patterns [66]. In the case of Ladakh's water sources, the diagram is used to examine the hydrochemical facies of the various water samples. These facies reflect the consequences of chemical interactions between the water and the minerals found in the lithologic framework (the geological materials forming the region).

Based on the data shown in Tables 1, 2, 5 and 8, the diagram provides a comparative review of the hydrochemical facies of different water sources in Ladakh (Fig. 3). The diagram reveals the dominant ions and their relative concentrations

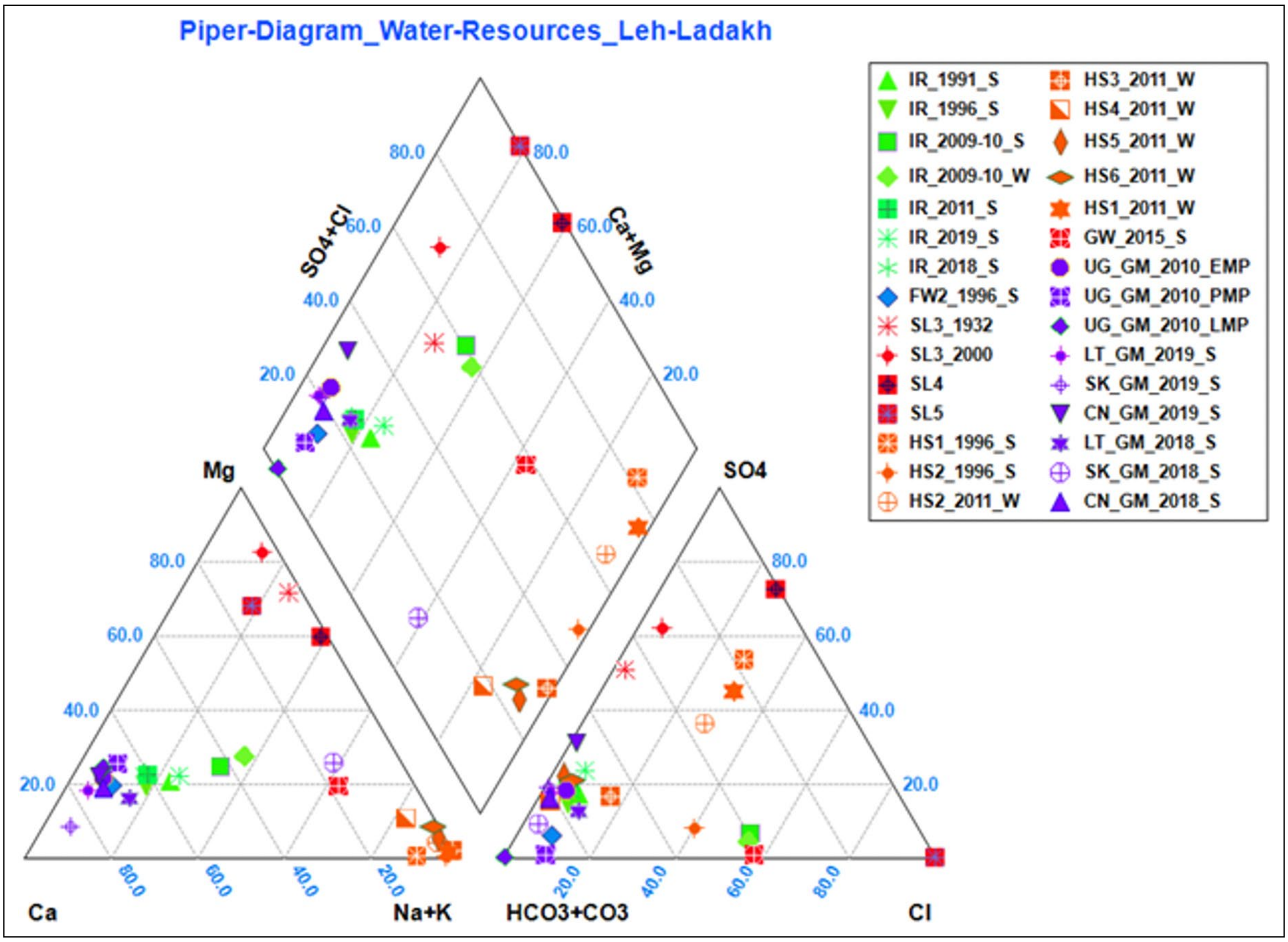


Figure 3. Piper diagram indicating ionic concentration of water samples collected from different regions of Ladakh. Data obtained and summarized from Ref. [13, 17, 30, 39, 40, 47, 51, 63–65, 96, 97].

in each water sample, indicating the type of weathering and the corresponding chemical facies. According to the diagram, freshwater lakes, and river water in Ladakh fall into the Ca^{2+}-Mg^{2+}-HCO_3^- type of facies, which indicates carbonate-type weathering. This suggests that the chemical composition of these water sources is influenced by the dissolution of carbonates present in the geological materials.

Hot water springs in Ladakh exhibit Na^+-K^+-Cl^--SO_4^{2-} and Na^+-K^+-HCO_3^- types of chemical facies. This suggests that the chemical composition of the water in these springs is primarily controlled by silicate weathering processes, where the dissolution of silicate minerals contributes to the presence of sodium, potassium, chloride, sulfate, and bicarbonate ions. Saline lakes in Ladakh display Ca^{2+}-Mg^{2+}-Cl^- and Ca^{2+}-Mg^{2+}-HCO_3^- types of facies. These facies indicate the prevalence of chloride and bicarbonate ions, along with calcium and magnesium ions, in the water samples. The presence of these ions indicates the influence of evaporative processes and the accumulation of salts in these saline lakes.

Durov Diagram

The trilinear Durov diagram, is a plot that is commonly used in hydrogeochemistry to analyse and compare the chemical composition of water samples, particularly in groundwater studies. This trilinear plot consists of two distinct triangular plots representing major cation and anion concentrations in water samples (Fig. 4). The concentrations of these ions are expressed in milliequivalents. The two triangular plots intersect at a common base, forming a rectangle. The purpose of the trilinear Durov plot is to visualize and analyse the chemical facies or composition of different water sources. By plotting the data points representing the chemical composition of water samples onto the rectangular grid at the base of each triangle, it becomes easier to identify patterns and variations in the composition. This plot provides a comprehensive representation of the water chemistry and allows for the comparison of different water sources based on their chemical characteristics. In addition to the main ion concentrations, two optional water quality metrics can be included in the plot. These metrics could be parameters such as pH, TDS, or electrical conductivity. By incorporating these metrics, the Durov plot allows for a direct comparison of multiple groundwater properties [67]. The Durov diagram, originally designed for groundwater water quality assessment, has been extended to evaluate quality of different water resources in Ladakh. The analysis includes groundwater, Indus River water, freshwater lakes, water from glacial melts, hot springs, and saline lakes.The dia-

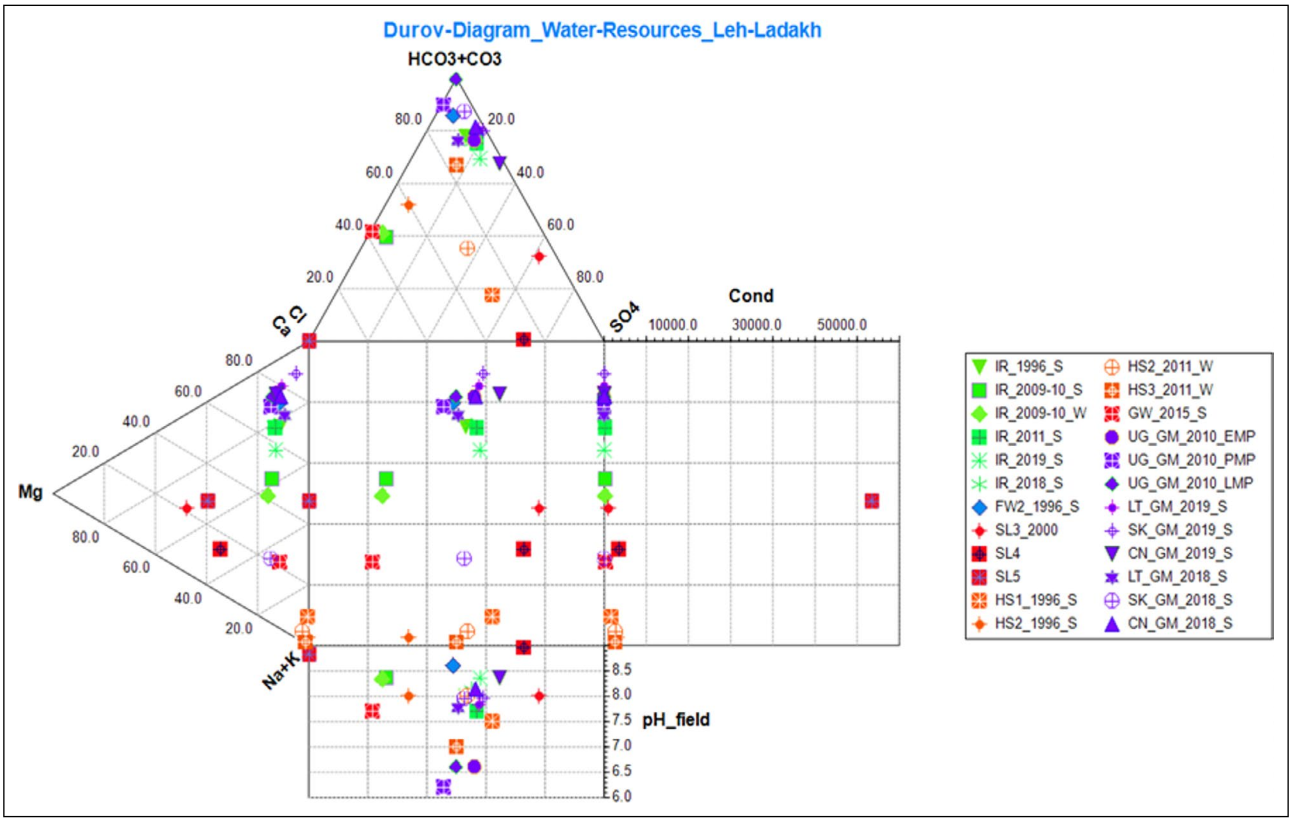


Figure 4. Durov diagram indicating water evolution pattern of water samples collected from different water resources of Ladakh. Data obtained and summarized from Ref. [13, 17, 30, 39, 40, 47, 51, 63–65, 96, 97].

gram reveals that groundwater, Indus River water, freshwater lakes, and water from glacial melts are characterized by the dominance of Ca^{+2} and HCO_3^- ions, indicating the prevalence of carbonate rock weathering. On the other hand, hot springs exhibit dominance in Na^+-K^+-Cl^--SO_4^{2-} and Na^+-K^+-HCO_3^- types of chemical facies. This observation suggests a different chemical composition associated with hot springs, potentially influenced by geothermal processes. Additionally, the prevalence of Ca^{2+}-Mg^{2+}-Cl^- and Ca^{2+}-Mg^{2+}-HCO_3^- types of facies in saline lakes aligns with the results obtained from the diagram. This confirms the chemical facies composition in saline lakes, where the dominant ions are calcium, magnesium, chloride, and bicarbonate. Furthermore, it can be deduced that water from groundwater, the Indus River, freshwater lakes, and glacial melts exhibits good quality with no contamination. However, water from hot springs and saline lakes indicates moderate to low quality, with high concentrations of sodium, chloride, and sulphate ions.

SUITABILITY OF WATER FOR AGRICULTURE

Only 20% of farmers in Ladakh have access to river water for irrigation, while the remaining 80% rely solely on glacier as their water source [12]. One of the primary uses of freshwater is for agricultural purposes, accounting for approximately 70% of annual global freshwater extraction [68]. The suitability of water for irrigation depends on the types and concentrations of dissolved salts present. The evaluation of irrigation water focuses on identifying unwanted elements, and its potential as a source of plant nutrients is considered only in specific circumstances. The United States Department of Agriculture (USDA) classification and various parameters such as Sodium Adsorption Ratio (SAR), Percent sodium (%Na), Residual Sodium Carbonate (RSC) and Corrosivity Ratio (CR) are utilized to determine the suitability of water for agricultural.Similarly,magnesium hazard (MH) is also one of critical parameter for estimating suitability of water for irrigation [69].

Sodium Adsorption Ratio (SAR)

Increased sodium content in water has a negative effect on soil characteristics and reduces soil permeability. When irrigation water has higher concentrations of Na^+ ion, it decreases soil absorptivity and leads to a deficiency of calcium, causing deflocculation and weakening of soil structure. To assess the suitability of water for irrigation and evaluate potential sodium-related risks, the sodium adsorption ratio (SAR) is used [70]. Figure 5 presents a salinity diagram (prepared by using Aquachem 10), plotting SAR against electrical conductivity (EC), which allows for the classification of irrigation water into different classes to determine its impact on soil salinity. The majority of Indus River samples and glacial melt water samples were classified as C1S1, indicating low salinity and sodium hazard, making them excellent for irrigation across various soil types (Table 9). Some Indus water and groundwater samples fell into the C2S1 class, indicating medium salinity hazard and low

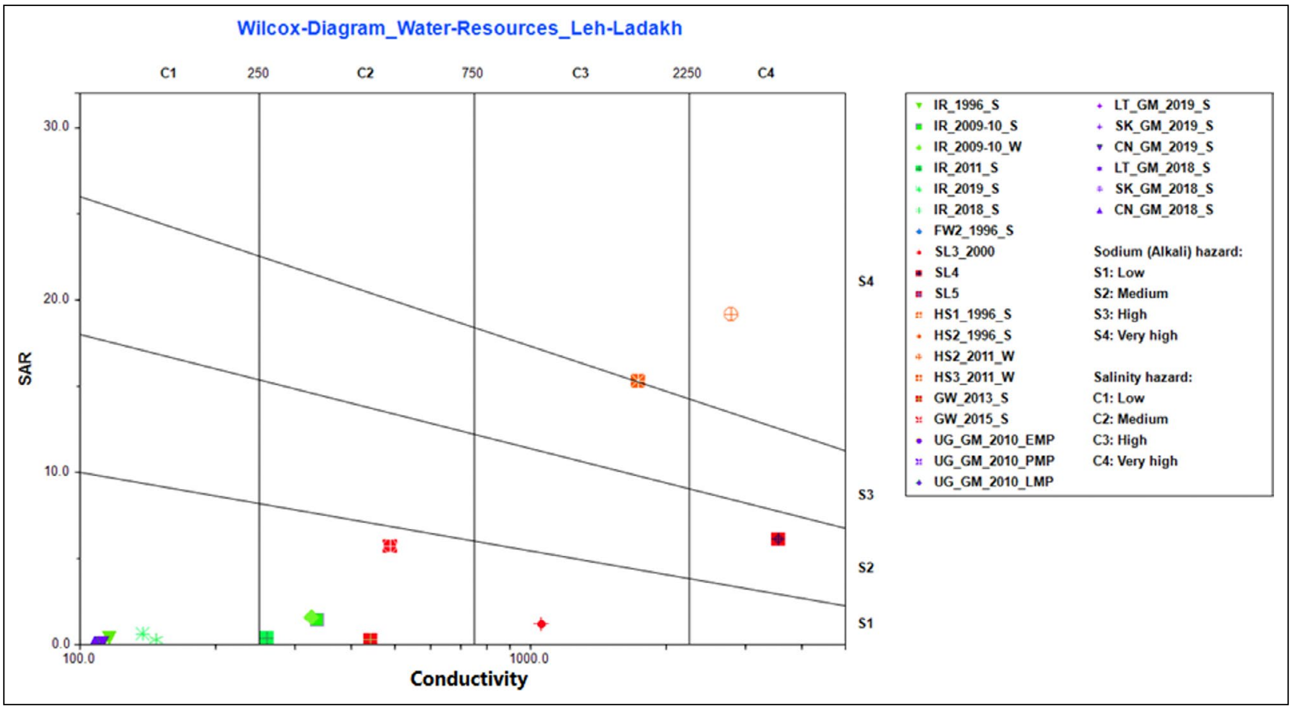


Figure 5. Wilcox diagram indicating sodium and salinity hazards of water samples collected from different water resources of Ladakh. Data obtained and summarized from Ref. [13, 17, 30, 39, 40, 47, 51, 63–65, 96, 97].

sodium (alkali) hazard, making them ideal for agricultural purposes. The water sample from the saline lake was categorized as C3S1, representing low alkali hazard but high salinity hazard, making it unsuitable for agricultural use. The hot spring water fell into the C3-C4S4 class, indicating very high alkali and salinity levels, making it unsuitable for agricultural purposes.

Residual Sodium Carbonate (RSC)

When there is an excess of carbonate compared to the levels of calcium (Ca) and magnesium (Mg), the extra carbonate combines with Ca and Mg and precipitates as solid material. As a result, the levels of Ca and Mg decrease, leading to an increase in SAR levels and the percentage of sodium. This, in turn, negatively affects the water quality for agricultural purposes. According to the value of RSC, the water quality is classified as <0 (very good), 0–2.5 (good), 2.5–5.0 (marginal), 5.0–7.5 (poor) and >7.5 (harmful) [71]. All the water sources except for hot springs were considered good to very good for agricultural use.

Percentage Sodium (%Na)

The percentage of sodium (%Na) is a significant factor to consider when examining the risks associated with sodium. The presence of sodium in soil leads to a decrease in soil permeability.The classification of water quality on the basis of sodium percent is given in Appendix 4 [72].

Magnesium Hazard (MH)

MH is a measurement that signifies the extent of harm caused to the soil structure due to the presence of magnesium in irrigation water. When the groundwater contains a high concentration of Mg^{2+}, it results in soil alkalinity. Additionally, a significant quantity of water gets adsorbed between magnesium and clay particles, thereby reducing the soil's ability to absorb water, which negatively affects crop growth. If MH exceeds 50, it indicates that the groundwater is detrimental and not suitable for irrigation. Conversely, if MH is less than 50, it suggests that the groundwater is appropriate for irrigation [72]. Based on MH all the river water, glacial melts, ground water and freshwater lake samples fall under suitable category for agricultural use while water hot springs and saline lake water fall under not suitable for agriculture (Table 9).

Corrosivity Ratio (CR)

The corrosivity ratio (CR) plays a crucial role in deciding whether water can be transported through metal pipes [38, 65]. When the CR value is below one, any type of metal pipe can be utilized for water delivery. Conversely, if the CR value exceeds one, water cannot be conveyed through metal pipes due to the higher risk of corrosion. Except for water sourced from saline lakes and hot water springs, the majority of water sources are generally appropriate for transportation through metal pipes in this region (Table 9).

IMPACT OF URBANIZATION

The National Geological Monument status has been conferred upon the varied geological features of the Himalayan region in Ladakh by the Geological Survey of India. Situated at an elevation of over 3000 meters in northwest India, Ladakh, also known as the "region of high passes," has become a sought-after tourist spot worldwide [23]. In recent

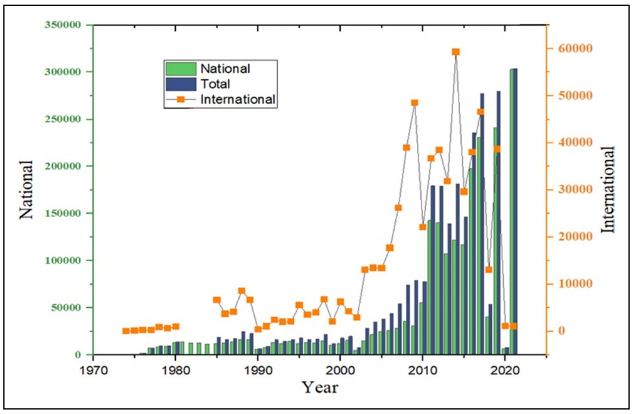


Figure 6. Tourists (national and international) arrival in Ladakh over last five decades. Data obtained from ref [75, 76].

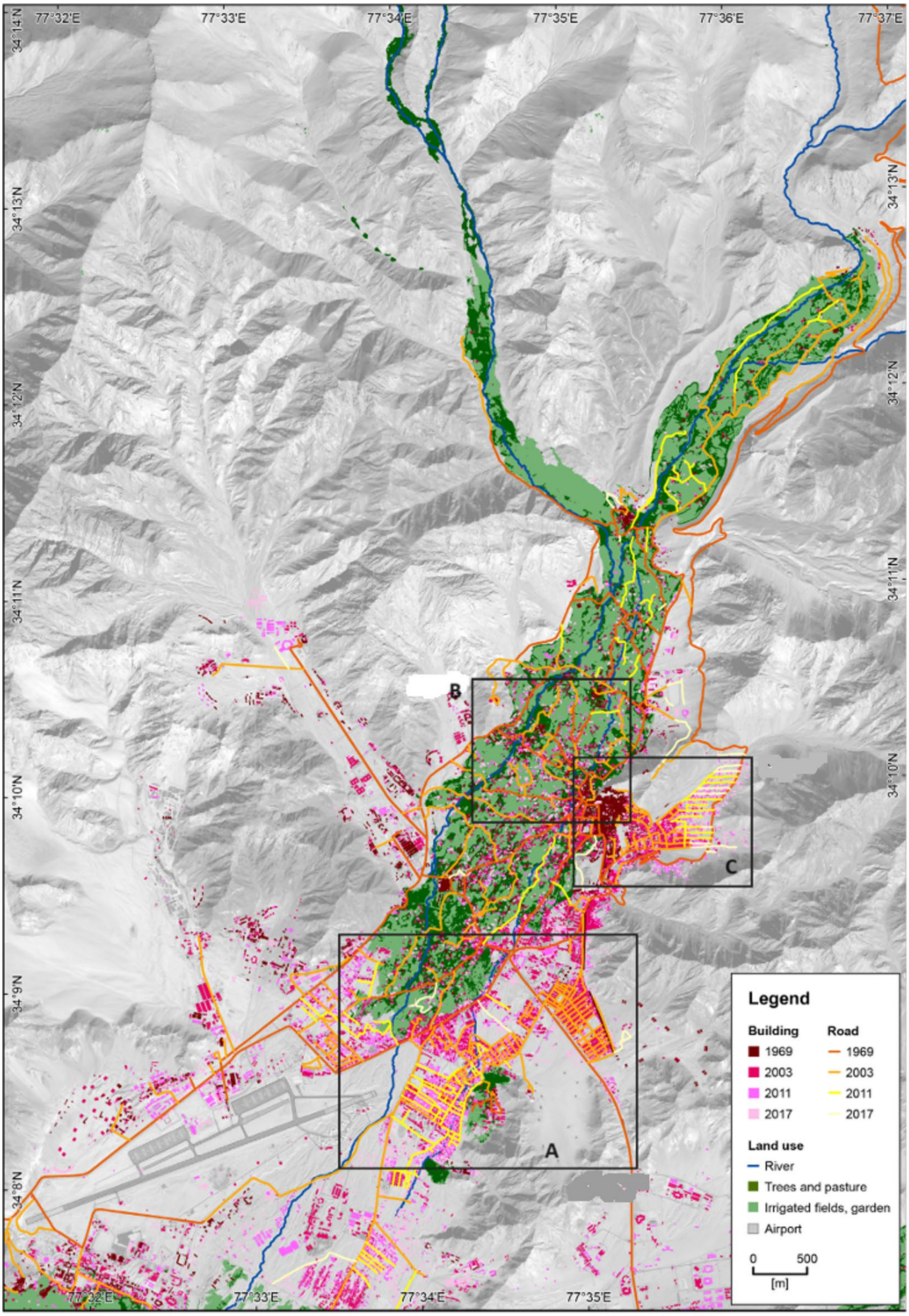
years, there has been a significant increase in urbanization and tourism in Ladakh, an environmentally vulnerable area. This rapid growth poses a serious threat to the region's environment, particularly in terms of water availability, which is further exacerbated by the impact of climate change [12, 14]. Despite its remote location, Ladakh is not immune to urbanization pressures, and both districts, Leh and Kargil, have experienced a steady rise in urbanization rates according to India's census reports from 1980, 2001, and 2011, with a decline of the rural population [7, 73]. The urbanization rates being 12.7, 23.4, and 34.2 in Leh and 5.3, 8.6, and 11.6 in Kargil, respectively, for these years. The Leh district has become one of the fastest urbanizing places in Ladakh due to its role as the administrative hub and the influx of floating populations such as army personnel and tourists [74]. The tourism industry plays a crucial role in Ladakh's local economy and has witnessed substantial growth since it opened its doors to foreign tourists in 1974. The number of visitors to Leh has multiplied over the years, with a significant increase observed between 2010 and 2022 (Fig. 6) [14, 75, 76]. This surge can be attributed to improved air connectivity and the expansion of domestic tourism driven by India's growing middle class. Despite the recent population increase, Ladakh's overall population remains relatively small (app. 2,75,000), with the majority residing in Leh and Kargil. However, due to security concerns related to neighbouring countries like China and Pakistan, an estimated 100,000 military personnel are stationed in Leh [12].

A study conducted in Lanzhou, a semi-arid region in China along the Yellow River, highlighted the degradation of groundwater quality due to arid climate conditions and excessive groundwater extraction [77]. Similar concerns arise in Ladakh, where rapid urbanization, driven by the booming tourism sector, may further deteriorate groundwater quality as it is heavily exploited to meet increasing demands. Some reports have revealed bacterial contamination in the spring-fed water pipeline system supplying the Chubi region of Leh. Although spring water has traditionally been considered safe for drinking in Ladakh, this contamination raises concerns about its reliability as a water source [74].

Asmoay et al. [78] studied the dry region of Nile Valley examined the impact of both natural factors and human activities on water contamination.The study found that 21% of the water samples analysed using the Water Quality Index were unsuitable for human consumption. Carcinogenic metals like lead (Pb) and cadmium (Cd), as well as total hardness, Na^{+}, K^{+}, Cl^{-}, and SO_4^{2-}, exceeded the acceptable ranges set by the WHO. In one of the towns of Leh district, there has been a significant departure from the traditional dry sanitation practice. The town has introduced water-intensive flush toilets and is disposing of untreated grey and black water in soak pits or septic tanks. However, the installation of a sewerage system is only partially functional and will take years to become fully operational [20, 74].This situation poses a huge threat of shallow groundwater pollution in the town. It is well known that even a minor change in the pH of water can accelerate the weathering of rocks, leading to changes in the chemical composition of water by increasing the dissolution of cations and anions [79]. This, in turn, results in elevated levels of TDS, turbidity, electrical conductivity (EC), and other parameters. Due to the heavy strain of tourism, the impact of these factors on the groundwater of this town is already evident. In the study, 75% of the samples showed higher levels of turbidity, and 10% exceeded the desired range for EC and TDS [74].

The tourism sector is predicted to experience significant growth as Odisha's Mayurbhanj district and the Union Territory of Ladakh have been recognized in TIME Magazine's '50 extraordinary destinations to explore' in their list of the 'World's Greatest Places of 2023' [80]. This acknowledgment highlights the appeal and uniqueness of these two Indian locations as tourist destinations. Some recent studies have examined the effects of rapid urbanization on water quality, particularly in semiarid regions and the results of which are summarized in Table 10 [3, 4, 8, 81–86].

UN-Habitat lists durable structures, population density, availability of clean water, access to better sanitation, and utility connectivity as some important markers of urbanization [87]. As mentioned previously availability of water in Leh is under heavy stress due to unplanned extraction of water resources especially groundwater by the ongoing climate change and anthropogenic processes of population expansion, urbanization, tourist influx, etc. Over the past few years, there has been a rapid expansion of housing settlements, encompassing both agricultural and barren lands, alongside a significant densification of urban areas. In one such report, 9400 new buildings were built between 2003 and 2017 alone, which is equal to the entire number built from 1969 to 2003 [88]. The overall built-up area grew almost five times during this time, from 36 hectares in 1969 to 196 hectares in 2017. As a result, from 1% in 1969 to 8% in 2017, the amount of agricultural land lost to building operations increased. A multi-temporal analysis of satellite imagery spanning from 1969 to 2017 illustrates the evolution of urban sprawl in Leh over the past fifty years as shown in Figure 7 and 8 [88]. A growing tourism industry, embrace of urban lifestyles, development of ad-



Satellite Images: Corona 30 Jul 1969, Quickbird 7 Nov 2003, 17 Jul 2006, Worldview 27 Nov 2011, Pléiades 22 Aug 2017
DEM: ASTER GDEM; Draft and Cartography: S. Schmidt, J. Dame, N. Harm

Figure 7. Urban development of Leh between 1969 and 2017. A: Housing Colony, Skalzangling and Ibex Colony constructed for residential purposes, B: Conversion of agricultural lands into built-up areas in Sankar and Chanspa, C: Residential and administrative quarter Skampari. Reproduced under Creative Commons License from an Open Access Article Ref. 88 (Elsevier).

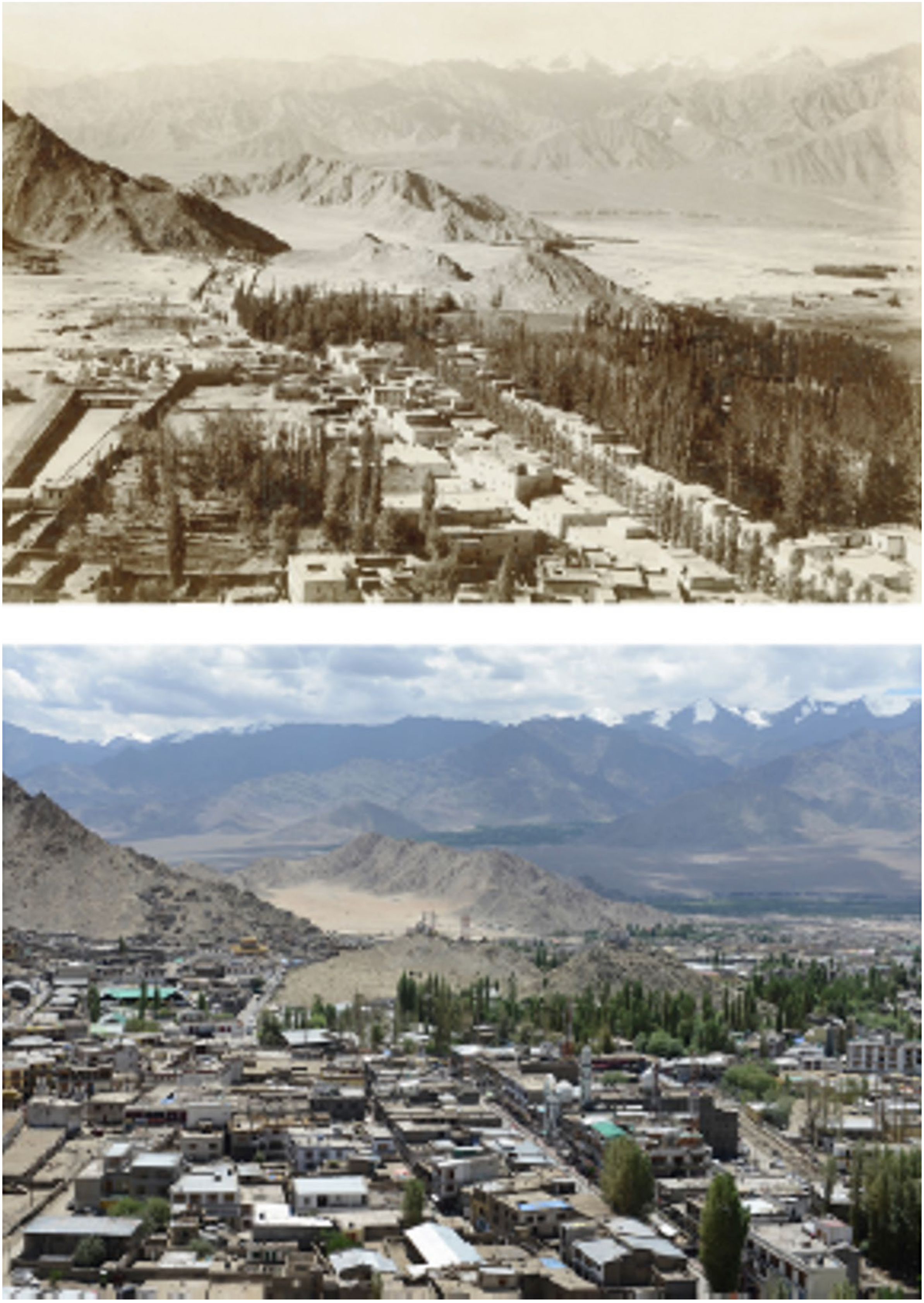


Figure 8. Repeat photography of Leh, taken from Tsemo Hill. The photographs show the axis of the main bazaar as a key urban structure. At the time of the early twentieth century, the large number of shops reflects the importance of trading activities for the small town. Recent urbanisation is characterised by intensive building activities in the centre and periphery of Leh, which reflects the growing diversity of services and functions for the region (upper photograph (a): C.G. Rawling 1903–1905; lower photograph (b): M. Nüsser 2013. Reproduced under Creative Commons License from an Open Access Article Ref. 88 (Elsevier).

Table 10. Recent studies on the impact of rapid urbanization on water quality with special reference to the semiarid areas

Sr. no.	Study region	Outcome	Ref
1.	Semi-arid region, Greece	A brief period of drought has the potential to trigger water crises in the region, creating a scarcity of water during the summer months. This may result in competition for water resources between tourists, rural activities, and even small-scale agricultural operations in the present and future.	[81]
2.	Liangjiang New Area, China	Urbanisation had detrimental consequences on macroinvertebrate community compositions in terms of taxonomic richness, diversity, and Ephemeroptera, Plecoptera and Trichoptera (EPT) species richness.	[82]
3.	Semi-arid Region of Northwest China	The study found that around 5.88% of the water samples were unsuitable for human consumption. The risk associated with water contamination was found to be significantly higher for children, indicating that they are more vulnerable to the effects of water pollution. Nitrogen and fluoride were identified as the most hazardous pollutants for human health in the region, caused largely by human activities such as the use of fertilizers, septic tank leakage, and discharge of organic matter into the water.	[83]
4.	Semi-arid environment of Essaouira Basin, Morocco	The water was not suitable for human consumption as it contained excessive amounts of calcium, magnesium, sodium, potassium, chloride, sulphate, bicarbonate and nitrate, as well as total dissolved solids that exceed the World Health Organization's standards. Research on nitrate pollution revealed elevated levels, which was attributed to three factors: (i) high level of tourism in the Sidi Kaouki area, (ii) lack of a proper sewage system and wastewater treatment facility, and (iii) discharge of animal waste during watering.	[84]
5.	Manali, Northern India	The rise in tourism has led to an increase in water consumption, resulting in the deterioration of water quality. The key pollutants responsible were sewage and solid waste. The population growth and urbanization caused a surge in sewage production, which is further exacerbated by the absence of a functional sewage treatment facility. This untreated sewage was directly discharged into the river, which is even worse than the conventional disposal method of letting sewage and grey water seep through the soil. The water quality downstream generally exhibited lower values of variables like BOD, DO, and TC compared to upstream, which can be partly attributed to urbanization and tourism.	[4]
6.	Tianchi scenic area of Xinjiang, China	Tourism-related activities significantly degraded the quality of surface water.	[85]
7.	Potrero de los Funes River, San Luis, Argentina	The average values of E. coli through all the studied periods exceeded the reference values established by the international organisms for recreational waters due to enriched nutrient level in water.	[3]
8.	Lidder River in Kashmir Himalayas, India	During the tourist season, the levels of nutrients such as nitrate nitrogen, ammoniacal nitrogen, total phosphorus, orthophosphate phosphorus, and BOD in the river were found to be alarmingly high. Apart from the sewage produced by hotels, guest houses, and residential areas, agricultural runoff was also a contributing factor to this issue.	[8]
9.	Semi-arid Coastal Aquifers, South Africa	A good percentage of water was found to be polluted by heavy metals such as lead, cadmium, and iron. Children were found to be at a higher risk than adults, as their hazard quotients (HQ) and hazard index (HI) was relatively higher.	[9]
10.	Semi-arid region of South India	The range of nitrate content in groundwater was 17 to 120 mg/L, with 57% of the samples surpassing the allowable limit. Agriculture and the discharge of human and animal waste were identified as the main causes of nitrate enrichment in groundwater. Additionally, it was shown that children in the study region had non-carcinogenic risks total hazard index (HI) that were 1.38 and 1.15 times greater than those for men and women, respectively.	[86]

ministration and infrastructure, and the region's geopolitical significance are some of the elements contributing to Leh's urban growth trend [88]. It has been observed that after the formation of Ladakh as Union territory, the developmental work has taken place at a very high pace but at the same time that has also increased vulnerabilities, including physical, sociocultural, economic, environmental, and climate-related threats [89]. A study revealed that interstate migration has doubled 1971 to 2011 in the UT of Ladakh and Leh dominates in interstate migrants [90]. In 2012–2013, a study utilized geographic information systems (GIS) to map point sources of water pollution in Leh, along with medical data analysis and surveys of households and hotels [91]. The findings suggested a potential link between groundwater pollution and increased occurrences of diarrhoea in the area over the past decade. Moreover, with over 80% of water demand being met by unregulated groundwater extraction, there's concern about depletion surpassing recharge rates. The study proposed leveraging GIS for informed urban planning and advocates for a partially decentralized sewage system to conserve water resources in Leh [91]. The study on anthropogenic climate change in the Ladakh Himalayas revealed a significant increase in greenhouse gases (GHGs), black carbon (BC), and pollutants from vehicular traffic near glaciers. The rise in temperatures, attributed to the heightened levels of GHGs and pollutants, has accelerated glacier melting in the region. If this trend persists, Himalayan glaciers could vanish entirely, leading to profound effects on regional water supplies, hydrology, ecosystem services, and transboundary water management [92]. The study conducted in the Alata River Basin based on climate change projections indicated a consistent rise in annual mean temperatures throughout the century, coupled with a decrease in precipitation across all future scenarios. These changes are expected to result in increased snowmelt and higher discharge generation, especially in the beginning and middle of the century. Similarly, a research performed in Leh demonstrated a warming trend in the climate, accompanied by reduced precipitation during the current decade [34]. Hence, Ladakh, being one of the ecologically fragile environments, faces a looming threat of water scarcity due to climate change and escalating anthropogenic pressures.

Climate change scenario studies offer valuable insights for devising mitigation and adaptation strategies. It is widely acknowledged that the impacts of climate change, and consequently the strategies for adaptation, differ from one location to another, contingent upon hydrological, socio-economic, and geographical factors. This underscores the imperative for investigating climate change impacts at the local level [93]. While this situation rapidly reduces the amount of groundwater, it also negatively affects its quality. Salinization, one of the most important factors affecting the quality of groundwater, is a global problem that is difficult to reverse. Thus, research and studies on the salinization of groundwater are important and imperative [94]. Table 11 summarizes different indicators of urbanization and their impact on the Ladakh region [7, 10, 12–14, 38, 59, 62, 73–76, 95–105].

CONCLUSION AND FUTURE RECOMMENDATIONS

In summary, Ladakh's rapid urbanization and thriving tourism industry pose significant environmental challenges, particularly in terms of water availability and quality. Since its opening to tourism in 1974, Ladakh has witnessed a significant influx of visitors, with tourist numbers soaring from 527 initially to approximately 531,396 in 2022. This surge, nearly double the local population of Ladakh, has led to the conversion of agricultural land for hotel construction. Over the years, the conversion of agricultural land has escalated from 1% in 1969 to 8% in 2017. Consequently, there has been a noticeable decline in the rural population, as the economy shifts from agriculture-based to tourism-driven. The unregulated extraction of groundwater and the transition from dry toilets to water-intensive flush toilets have exacerbated water quality degradation. Reports indicate an increase in dissolved solids concentration over time, highlighting the environmental challenges arising from rapid tourism growth in Ladakh. Instead of relying solely on reactive measures to address the damage caused, it is crucial to implement preventive policies from the outset of the planning process. Sensible policies should be adopted to tackle the problems arising from the increasing tourism, such as educating tourists about the environment, implementing tourist taxes, promoting the use of compost toilets as an alternative to water-intensive flush toilets, and possibly regulating the number of tourists visiting the area. Efforts are needed to address these issues and ensure sustainable development in the region.

To ensure sustainable urbanization and tourism, it is essential to implement both short-term and long-term policies to conserve the limited water resources in the region. GIS can play a vital role in assessing water quality and promoting sustainable tourism development. By utilizing GIS, a versatile platform that integrates and analyses diverse information, stakeholders can gain a comprehensive understanding of water bodies. This will enable them to make well-informed decisions and effectively manage and preserve these resources for sustainable tourism [11]. Therefore, it is important to promote the use of GIS-based water quality assessment for sustainable tourism and urbanization.Further, it is crucial to extend studies beyond the Leh district in Ladakh and examine the impact of urbanization and tourism in other areas as well. Currently, most research has focused on Leh due to its accessibility by air, while other significant places such as Kargil have been overlooked.

The most challenging aspect of managing the water supply in the Ladakh region in the face of future climate change is predicting and preparing for the potential effects of global warming on precipitation and temperature patterns. In recent decades, Leh has experienced a rapid increase in temperature and unpredictable precipitation. The changing climate in the Leh region will have adverse and potentially irreversible impacts on both the natural environment and human activities [34]. Therefore, it is crucial for the administration to strictly implement measures to mitigate global warming, achieve the goals of 100% carbon neutrality, and preserve glaciers in the region. Encouraging the implementation of artificial glaciers

Table 11. Impact of urbanization on water quality with special reference to Ladakh

Indicators of urbanization	Reason	Impact	Reference
Enhanced constructional activities		•Rapid expansion of housing settlements, encompassing former agricultural and barren lands. •The overall built-up area increased from 36 hectares in 1969 to 196 hectares in 2017. •Agricultural land lost to construction rose from 1% in 1969 to 8% in 2017.	[12, 13, 102]
Overcrowding		•Army and tourism in the floating population a significant factor contributing to urbanization in Leh Ladakh. •Census reports of India from 1980, 2001, and 2011, show a decline in the rural population and an enhanced urban population. •Leh town has been reported as the fastest urbanizing place in Ladakh. •Significant increase in tourism every year. In 2022 the tourist inflow increased 17 folds to 5,31,396 (Fig 6).	[7, 12–14, 59, 73–76, 102, 103]
Issue of access to safe water	Growing tourism industry, urban lifestyles, infrastructure development, administrative and geopolitical significance.	•Unequal access to water resources leads to social and environmental changes, harming water quality and availability. •Increased amount of microplastic in Indus River water as compared to other major Rivers of India. •Groundwater found significant pollution due to the accumulation of Cr, Cd, Ni, Mn, Fe, and Cu. •Cd, As, and Pb found above the WHO's permissible limit in the Indus River, irrigation water, and stagnant water at various locations in Leh. •Higher levels of Mg, Na, K, Mn, Ca, Cl, S, and Al were found in the Indus River water collected near the city area of Leh as compared to previous studies with concentration of Al and alkalinity exceeding the limits prescribed by the WHO. •Anthropogenic activities and agricultural waste are the main factors affecting the water quality of the Indus River and the effects are more prominent during the summer season, indicating the impact of tourism on water quality. •The recent surge in urbanization and tourism is found to threaten the fragile environment, especially water availability, worsened by climate change. •Reports have uncovered bacterial contamination in the spring-fed water pipeline system serving the Chubi region of Leh. While spring water has historically been trusted for drinking in Ladakh, this contamination casts doubt on its reliability as a water source. •In the study, 75% of the samples of groundwater showed higher levels of turbidity, and 10% exceeded the desired range for EC and TDS. •Increased occurrences of diarrhea in the area over the past decade. Moreover, with over 80% of water demand being met by unregulated groundwater extraction, with concern about depletion surpassing recharge rates	[12, 14, 38, 59, 62, 74, 104]
Improved sanitation		In Leh town, there has been a notable shift from traditional dry sanitation to water-intensive flush toilets. Untreated grey and black water is disposed of in soak pits or septic tanks due to a partially functional seweage system, posing a serious threat to groundwater contamination.	[10, 74]
Increasing traffic issue		With the anticipated surge in tourism and population leading to increased vehicle traffic, air pollution is expected to rise. A study conducted near the national highway in Ladakh reveals a significant impact on glacier melting attributed to the increase in greenhouse gases (GHGs) and black carbon (BC) emissions.	[92, 105]

at the village level should also be promoted. The pressures of urbanization are expanding beyond Leh town to other parts of Ladakh, notably the Kargil district. Between 1965 and 2020, the built-up area increased over ninefolds, with the urban population of Kargil town soaring from 1681 in 1961 to 16,338 in 2011 [95]. This necessitates extending research efforts to encompass various towns and regions across Ladakh. Such studies can offer a deeper insight into hydrochemical dynamics and the effects of urbanization on water quality, facilitating informed decision-making and sustainable planning strategies for the entire region.

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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.

USE OF AI FOR WRITING ASSISTANCE

Not declared.

ETHICS

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

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APPENDICES

Appendix 1. Classification of water quality based on electrical conductivity [53]

Electrical conductivity (µS/cm)	Classification	Source of water
<1500	Permissible	Groundwater, River water and Freshwater lakes
1500–3000	Not permissible	Hot springs
>3000	Hazardous	Saline Lakes

Appendix 2. Classification of water quality based on total dissolved solids [53]

Total dissolved solids (mg/L)	Classification	Remarks
<1000	Fresh water type	Groundwater, River water and freshwater lakes
1000–10000	Brackish water type	Hot springs and Saline Lakes
10000–100000	Saline water type	–
>100000	Brine water type	–

Appendix 3. Classification of water quality based on total hardness [53]

Total hardness as $CaCO_3$ (mg/L)	Classification	Remarks
<75	Soft	Groundwater, River water and freshwater lakes
75–150	Moderately high	
150–300	Hard	Hot springs and saline lakes
>300	Very hard	Hot springs and saline lakes

Appendix 4. Classification on the basis of sodium percent [72]

Sodium percent	Suitability for irrigation	Remarks
<20	Excellent	None
20–40	Good	Most of the river water, glacial melts, ground water and freshwater lake fall under good to permissible limit.
40–60	Permissible	
60–80	Doubtful	Some ground water ample during tourist season are also in doubtful category.
>80	Unsuitable	Water from hot spring is unsuitable.