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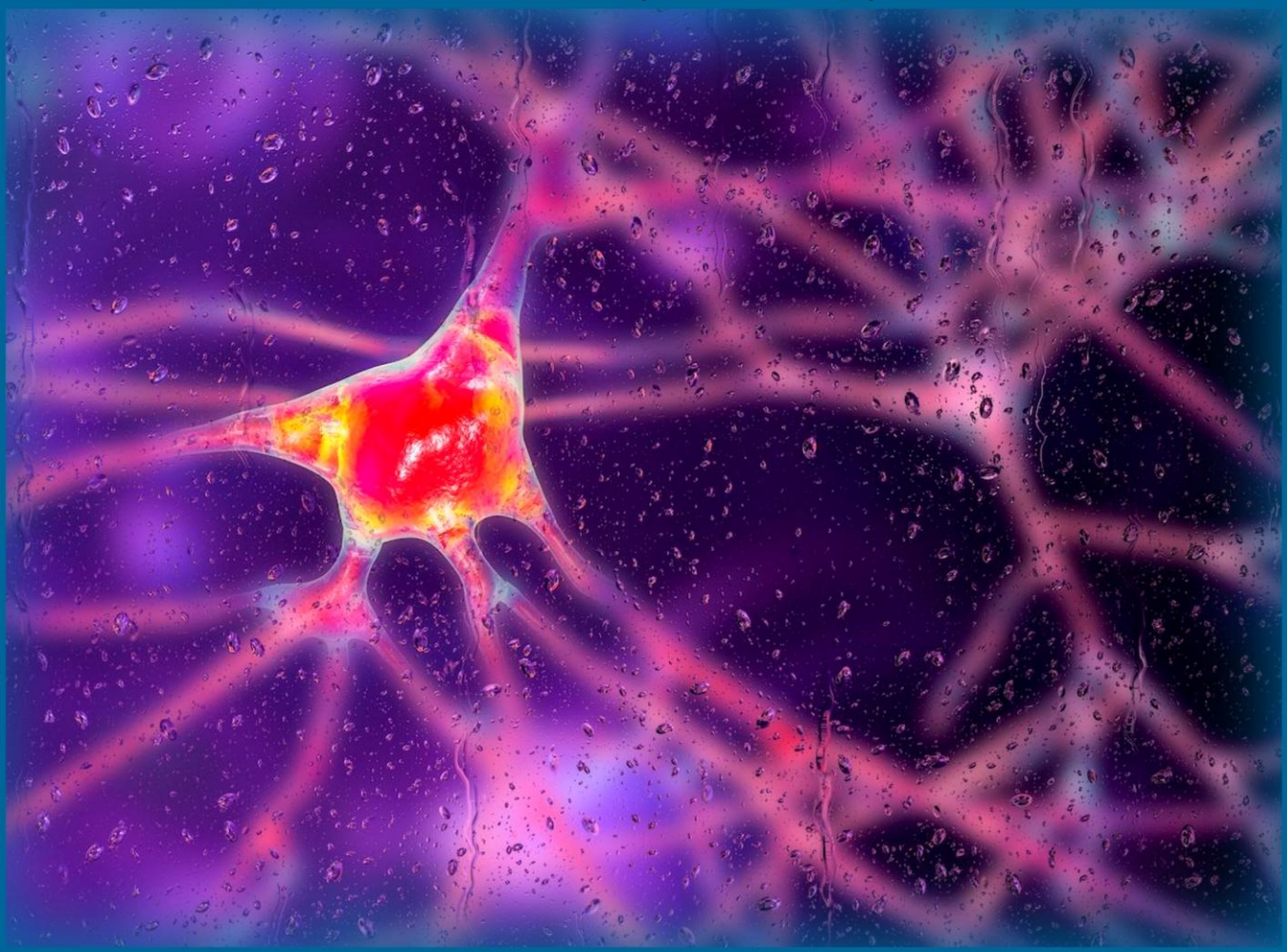
"Huntington's disease treated successfully for first time in UK gene therapy trial" The Guardian



Huntington's disease is an inheritable condition that causes brain cells to die. A new gene therapy may help slow the disease's progression, trial data suggest.
(Image credit: KATERYNA KON/SCIENCE PHOTO LIBRARY via Getty Images)

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DRIVING SAFETY AND COMFORT: A BIBLIOMETRIC ANALYSIS OF THE ROLE OF AUTOMOBILE HEADLIGHTS

SÜLEYMAN GÖKOVA *[1]

Abstract: This study analyzes research trends in vehicle headlights, focusing on publications related to driving safety and comfort. The research aims to reveal the developments in headlight technologies, the effects of lighting performance on driving safety and comfort, the use of headlights in different road and weather conditions, and the general trends in scientific studies on these subjects. A combined quantitative and visual analysis approach is used to comprehensively understand the intellectual accumulation, citation patterns, influential researchers, and the evolution of research themes over time. The analysis covers 953 publications, from which a sample of 241 was selected using the keywords "vehicle or car and headlight or headlamp," and reveals a recent increase in research activities, especially in 2021-2024, reflecting the automotive industry's emphasis on advanced driver assistance systems and innovative lighting technologies. Multi-authored publications were found to have higher citation counts, demonstrating the value of collaboration. Temporal distribution analysis shows an increasing research interest in vehicle headlights. The findings highlight key influencers and collaboration networks within the field, emphasizing the importance of international partnerships in addressing common challenges related to road safety and driving innovation. This study provides insights into emerging research trends and potential gaps, guiding future research directions in the pursuit of safer and more comfortable driving experiences.

Keywords: Automobile Headlights, Driving safety, Driving comfort, Bibliometric analysis.

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1. INTRODUCTION

The safety of drivers during nighttime travel is a pressing concern that merits significant attention, particularly as night driving is associated with higher accident rates compared to daytime conditions. One crucial aspect of this safety challenge is nighttime sight distance, which remains inadequately addressed in current highway design guidelines. Traditional two-dimensional models used to assess sight distance often fail to account for the complexity of various roadway alignments and roadside obstructions, leading to potential misestimations of visibility (César et al., 2016). Furthermore, innovations in headlamp technology have the

potential to significantly improve driver safety. For instance, a Smart Headlamp system can reduce instances of temporary blindness caused by oncoming headlights, a common occurrence during night driving (Fechtner et al., 2019; Toney & Bhargava, 2021). By exploring both design and technological advancements in headlamps, this investigation aims to enhance our understanding of factors influencing driver safety at night and propose necessary improvements for future vehicle technology.

1.1. Importance of headlamp functionality in ensuring driver safety

The functionality of headlamps is critical for ensuring driver safety, particularly in low-light and adverse weather conditions. Effective illumination not only enhances visibility for the driver but also serves to alert other road users to the vehicle's presence. Poorly functioning headlamps can obscure road hazards, increase the likelihood of collisions, and significantly compromise the overall safety of nighttime driving. Moreover, advanced technologies, such as those simulated through digital twins, can be utilized to optimize headlamp performance by accurately replicating light effects and assessing various driving scenarios (Dawid et al., 2024). Furthermore, the increasing complexity of modern vehicles necessitates a thorough understanding of headlamp functionality in the context of vehicle cybersecurity, as any vulnerabilities could lead to malfunctions that endanger driver safety (Merola et al., 2024). Thus, a rigorous approach to headlamp functionality is essential for maintaining safe driving practices and reducing accident rates.

1.2. Types of headlamps

An understanding of the different types of headlamps is crucial for enhancing driver safety, particularly during nighttime travel. Headlamps can be categorized primarily into halogen, LED, and HID (High-Intensity Discharge) types. Halogen headlamps are the most traditional and provide adequate illumination; However, they consume more energy and have a shorter lifespan compared to their modern counterparts. LED headlamps, on the other hand, offer increased energy efficiency and a longer operational life due to their lower heat production and durability. This is especially pertinent considering that nearly 50 percent of fatal motor vehicle crashes occur at night, often attributed to reduced visibility and reliance on visual cues, This fact emphasizes the critical role of effective lighting in driver safety (Franz, 2009). Additionally, advancements such as on-road projections can provide visual communication between vehicles and pedestrians, thereby enhancing situational awareness and reducing distraction for drivers (Glück et al., 2021).

1.3. Comparison of halogen, LED, and HID headlamps in terms of visibility and safety

The ongoing evolution of automotive lighting technology, particularly halogen, LED, and HID headlamps, presents significant implications for visibility and safety on the road. Halogen headlamps have traditionally been favored for their affordability and adequate visibility but fall short in efficiency and luminosity compared to emerging alternatives. In contrast, LED headlamps offer improved illumination and a longer lifespan, yet their intense brightness can lead to increased glare for oncoming drivers, especially older adults who are more susceptible to visual discomfort and decreased performance under glare conditions, as highlighted by research demonstrating the adverse effects of HID headlights on visual acuity across different age groups (Friedland, 2012). Furthermore, the broad spectrum of light emitted by these advanced headlamp types also risks ecological disruption, drawing attention to the need for balanced designs that mitigate glare while prioritizing safety (Gaston et al.). As vehicle

manufacturers refine these technologies, the integration of glare-mitigation strategies is essential to enhance driver safety.

1.4. Maintenance and regulations

Effective maintenance and adherence to regulations are crucial for ensuring driver safety, particularly regarding vehicle headlamps. Properly functioning headlamps significantly enhance visibility, especially during nighttime driving when the majority of fatal accidents occur due to reduced visual cues on the road (Franz, 2009). Regulatory frameworks, such as the new MUTCD standards on traffic sign retro reflectivity, aim to address these safety concerns by improving nighttime visibility for drivers (Franz, 2009). Furthermore, advancements in automotive design emphasize the integration of sustainability with functionality, prompting manufacturers to adopt life cycle thinking approaches that prioritize both performance and environmental impact. This dual focus not only addresses the immediate safety needs of drivers but also promotes long-term sustainability within the automotive sector. By complying with established maintenance protocols and regulations, drivers can ensure their headlamps operate optimally, thereby enhancing overall road safety and contributing to a more responsible driving culture.

1.5. Overview of headlamp maintenance practices and legal requirements for vehicle safety

In the context of vehicle safety, headlamp maintenance practices are essential for ensuring both driver visibility and compliance with legal standards. Regular inspections of headlamps are necessary to guarantee their functionality, as malfunctioning lights can severely impair vision, especially during nighttime driving, leading to potentially hazardous situations on the road. Moreover, the legal requirements mandate that vehicle headlamps must operate within specified brightness standards to enhance road guidance for drivers, as inadequate lighting can contribute to accidents due to poor visibility (Vrábel et al., 2023). Additionally, the automotive industry's commitment to sustainable practices, as outlined in various initiatives, underscores the importance of integrating eco-friendly materials and designs in headlamp production, thereby aligning with broader environmental goals (Brumbelow, 2022). Consequently, adherence to these maintenance practices and legal specifications not only promotes driver safety but also supports the ongoing transition towards more sustainable vehicle technologies.

In conclusion, the effectiveness of vehicle headlamps plays a pivotal role in ensuring driver safety, particularly during nighttime driving conditions. As the analysis reveals, many accidents stem from human errors exacerbated by inadequate lighting or obstructions in visibility caused by oncoming traffic headlights. The integration of advanced technologies, such as Smart Headlamp systems, could significantly reduce the risk of high beam blindness, allowing drivers to make safer overtaking decisions (Toney & Shety, 2021). Moreover, understanding the challenges faced by different vehicle types, particularly those with higher eye levels such as trucks, underscores the necessity for specific adaptations in headlamp design (Sivak et al., 1993). By prioritizing these technological enhancements and tailoring safety features to accommodate varied driving scenarios, we can enhance road safety and mitigate the risks associated with nighttime driving. The collective responsibility of manufacturers, policymakers, and drivers is essential for fostering a safer driving environment.

1.6. Summary of the impact of headlamp technology and maintenance on overall driver safety

The efficacy of headlamp technology and diligent maintenance practices significantly influences overall driver safety, particularly during nighttime driving conditions. Approximately 50 percent of fatal motor vehicle crashes in the United States occur at night, highlighting the critical need for effective illumination systems that enhance visibility and inform drivers of their surroundings (Franz, 2009). Advanced headlamp technologies, such as adaptive lighting and LED systems, provide drivers with improved visibility by better illuminating road conditions and potential hazards. Moreover, the regular maintenance of headlamps, including the replacement of burnt-out bulbs and the cleaning of lenses, can prevent debilitating visibility issues that could contribute to accidents. As the automotive industry moves toward sustainable practices, integrating environmentally friendly materials and efficient technologies into headlamp design reflects a broader commitment to driver safety and environmental responsibility (Maltese, 2019). Ultimately, the marriage of advanced headlamp technology and responsible maintenance is paramount for enhancing driver safety on the roads.

Road safety is a critical concern in the field of transportation, with factors such as vehicle design, infrastructure, and driver behavior playing a key role in determining the safety and comfort of road users. Among these factors, the role of vehicle headlights has received significant attention from researchers, as they are essential for visibility and safety, particularly in low-light conditions (Brumbelow, 2022); Vrábel et al., 2023).

Existing literature has explored various aspects of headlight technology and its impact on driving safety and comfort. These studies have highlighted the importance of real-time safety metrics for automated driving systems, the need to accommodate the human element in transportation systems, and the potential of intelligent headlight control systems to enhance visibility and reduce accidents.

The research landscape in this field is diverse, with studies examining topics ranging from the development of automatic headlight leveling systems (Fechtner et al., 2019) to the detection of oncoming vehicles for intelligent headlight control (López et al., 2008). However, a comprehensive bibliometric analysis of the research trends, key contributors, and influential publications in this domain is lacking.

This bibliometric study aims to provide a holistic understanding of the research landscape surrounding the role of headlights in driving safety and comfort. The analysis will identify the most influential publications, the leading researchers, and the emerging trends in this field, offering valuable insights for researchers, policymakers, and industry stakeholders.

1.7. Bibliometric analysis

Bibliometric analysis is a research method employing statistical and mathematical tools to examine large bodies of scholarly literature. It quantifies aspects of publications, such as authorship, citations, keywords, and publication venues, to reveal patterns and trends within a specific field of study (Yan & Zhiping, 2023). This quantitative approach allows researchers to map the intellectual landscape of a topic, identify influential authors and publications, track the evolution of research themes, and gain insights into the overall structure and dynamics of academic discourse (Whitney et al., 2019). By analyzing citation patterns, bibliometric analysis can reveal the impact of specific works and authors, as highly cited articles are generally considered to be influential contributions to the field (Xie et al., 2020). Furthermore, bibliometric analysis can uncover emerging research areas and highlight potential gaps in

existing knowledge (Cipollina et al., 2021). This methodology offers a valuable means of understanding the historical development, current state, and potential future directions of a given research area.

2. MATERIAL AND METHOD

A combination of citation analysis, co-authorship patterns, and keyword co-occurrence was utilized to identify the most influential publications, key research topics, and emerging trends in the field of headlights and driving safety.

An important database, such as Web of Science, was searched using keywords related to "headlights", "driving safety", and "driving comfort". The citation patterns of the retrieved publications were analyzed to identify the most influential works in the field. Additionally, the co-authorship networks were examined to uncover the collaborative dynamics among researchers, as well as the keyword co-occurrence to map the thematic structure of the research.

The research was conducted on February 12, 2025, selecting all years and all Web of Science indices in the filtering area. As a result of this search, 241 articles were found and these 241 articles were selected as a sample (http://apps.webofknowledge.com, Access Date: 12.02.2025).

The bibliometric analysis method was adopted in the study, and the VOSviewer program was used to examine the publications. Publication year, most frequently used keywords, country with the most publications, researcher with the most publications, researcher with the most co-authorships, country with the most citations, and researcher with the most citations are provided for the 241 publications examined. In addition, visual analysis was performed by creating network maps and the obtained findings were discussed.

2.1. Data Collection and Search Strategy

The publications for this bibliometric analysis were collected from the Web of Science (WOS) Core Collection database, provided by Clarivate Analytics. To clearly define the scope and thematic focus of the study, a detailed search strategy was established, encompassing both general Topic terms and specific Citation Topics Micro.

The primary search query applied was as follows:
"(vehicle OR car) AND (headlight OR headlamp) (Topic) AND (4.183.669 Road Safety OR 4.169.2376 Light Pollution OR 4.17.128 Deep Learning OR 4.183.486 Traffic Flow OR 1.36.813 Myopia OR 1.36.212 Retina OR 7.300.908 Asphalt Mixture OR 1.5.1090 Fear Conditioning OR 1.247.461 Migraine OR 1.129.98 Low Back Pain OR 6.73.1369 Evolutionary Psychology OR 4.284.2778 Artificial Intelligence OR 4.29.104 Adaptive Control OR 4.48.322 Semantic Web) (Citation Topics Micro)"

To ensure the academic credibility and relevance of the retrieved results, the publications were further filtered by applying the following WOS index restrictions:

- SCI-EXPANDED (Science Citation Index Expanded)
- SSCI (Social Sciences Citation Index)
- A&HCI (Arts & Humanities Citation Index)
- ESCI (Emerging Sources Citation Index)

- CPCI-S (Conference Proceedings Citation Index – Science)
- CPCI-SSH (Conference Proceedings Citation Index – Social Science & Humanities)
- BKCI-S (Book Citation Index – Science)
- BKCI-SSH (Book Citation Index – Social Science & Humanities)

This comprehensive filtering strategy was designed to include interdisciplinary publications closely related to the research area, such as those from engineering, computer science, traffic psychology, and visual sciences. The total number of publications retrieved through this precise strategy formed the basis of our analysis.

2.2. VOSviewer

VOSviewer is a software tool for constructing and visualizing bibliometric maps. These maps represent the relationships between different academic entities, such as authors, publications, or keywords. By analyzing co-occurrence, co-citation, or bibliographic coupling, VOSviewer creates network visualizations that reveal clusters of related items, highlighting key themes, influential works, and collaborative patterns within a research area (Van Eck & Waltman, 2017).

3. RESULTS

In the visualization provided by VOSviewer, each circle represents an item selected according to filtering criteria determined by the researcher (Van Eck & Waltman, 2009). This item could be a country, author, document, term, or similar data point. The size of the circle indicates the frequency of occurrence of the corresponding item; the largest circle represents the most frequently occurring item. Items are color-coded and clustered into groups according to their occurrence scores (Bukar et al., 2023). While each item can only belong to one cluster, it's also possible for some items not to belong to any cluster (Girvan & Newman, 2002). The lines between the items represent the strength of the connections. Thin lines indicate weaker connections, while thicker lines represent stronger connections (VOSviewer - Visualizing Scientific Landscapes, 2023). This visualization method offers a useful tool for understanding the complex structure and relationships within scientific research (Van Eck & Waltman, 2009; VOSviewer - Visualizing Scientific Landscapes, 2023). VOSviewer is a software frequently used, especially in bibliometric analyses, assisting researchers in mapping research areas, identifying trends, and highlighting key actors (Bukar et al., 2023; Husaeni & Nandiyanto, 2021). This type of analysis is particularly valuable in rapidly evolving fields, such as digital learning, for evaluating research performance and setting directions for future studies (Husaeni & Nandiyanto, 2021).

3.1 Keyword analysis

Figure 1 illustrates the keywords used in publications on "driving safety and comfort" and "car headlights" indexed in Web of Science. From a total of 2640 keywords, 68 were selected based on a minimum frequency of five occurrences. The most frequent keyword is "vehicle detection" (35 occurrences), followed by "LED" (26 occurrences). Other prominent keywords include "headlamp," "headlight," "glare," "headlights," "visible light communication," "automotive lighting," and "road safety." Notably, variations of "headlight" (headlamp, headlights, car headlights, vehicle headlights, headlamps, vehicle headlamps) collectively appear 89 times.

This visualization, generated using VOSviewer, maps the most frequent keywords in publications on these topics. The graphic visualizes current research trends and focal points

within the field. Keyword size represents relevance and frequency, with larger words indicating greater importance. Keyword proximity reflects conceptual relationships; closer words suggest concepts often discussed together. The analysis reveals that "driving safety and comfort" and "car headlights" are prominent themes, representing key areas of research focus.

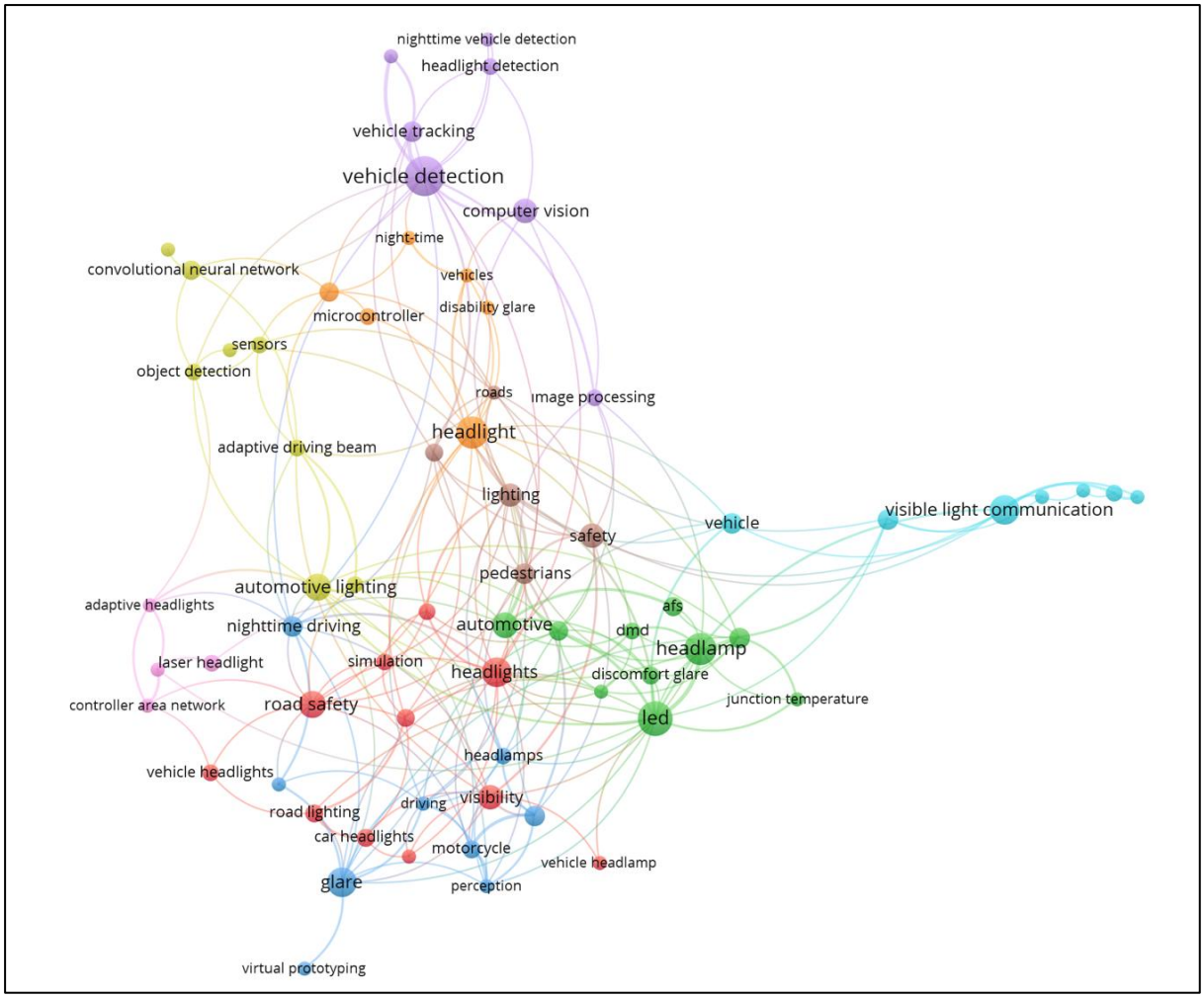

Figure 1. Keyword analysis

This graph in Figure 3.1 reveals the strong relationships between research topics in the field of vehicle lighting technology. The red and orange clusters in the center show how closely headlights and lighting systems are connected to topics like road safety and adaptive driving. Furthermore, the purple cluster on the top left shows that topics such as vehicle detection, computer vision, and artificial neural networks play a critical role in the development of lighting systems, especially for nighttime driving. The green and blue clusters on the right focus on the more technical aspects of LED technology, namely thermal topics like junction temperature and innovative applications like visible light communication.

3.2. Most co-authorship analysis

Figure 2 presents the researchers with the most co-authorships. A total of 2995 researchers were identified in the publications analyzed. Of these researchers, 21, who had at least 1 publication and at least 5 citations, were considered. The color of the area containing the researchers' names in the figure varies according to the number of co-authorships. Blue indicates a small number of co-authorships, while yellow indicates a larger number of co-authorships. Examining the

figure, it can be seen that the researcher with the most co-authorships is Chi, Nan(38). This researcher is followed by Lin, Shih-Kang, Sun, Ching-Cherng, Wu, Chi-Shou, Yang, Tsung-Hsun(34), and Yu, Yeh-Wei (29), in order.

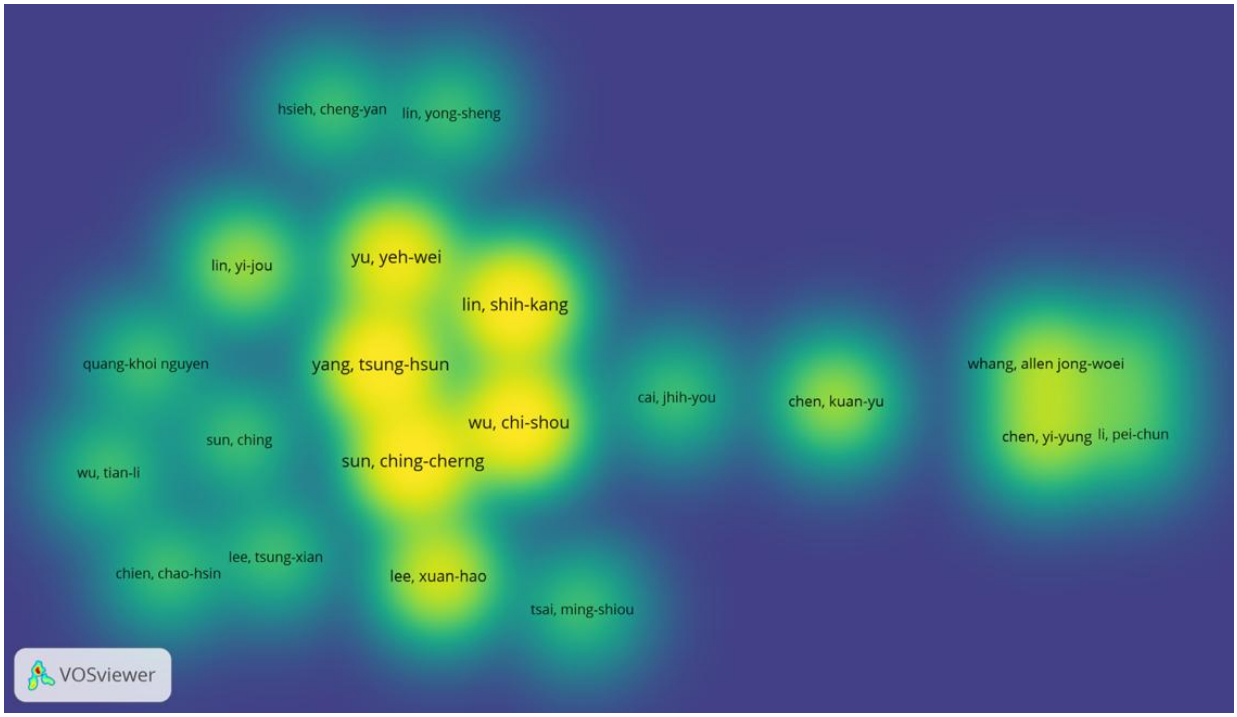

Figure 2. Researchers with the most co-authorships

The density visualization in Figure 2 effectively maps the researchers and groups with the strongest co-authorship relationships within a specific scientific or academic field. The color intensity, transitioning from yellow to green and purple, indicates the frequency and strength of collaboration between an author and others in the network:

The Central and Most Dense Cluster (Yellow Area): The brightest and most central region of the map represents the tightest and most productive co-authorship network, formed by authors such as Yang, Tsung-hsun, Lin, Shin-kang, Sun, Ching-cherng, and Wu, Chi-shou. These authors have collectively produced the most publications on core research topics in the field, making them the core actors of the ecosystem.

Peripheral and External Groups (Green and Purple Areas): The decrease in density towards the map's edges indicates authors who collaborate less frequently or within smaller, more isolated groups. For example, the cluster led by Whang, Allen Jong-woei is separated geographically or thematically from the central group but maintains strong internal collaboration. Such groups are typically peripheral actors with weaker ties to the main network or focus on different subtopics.

Collaboration Strategy Insight: This map highlights that the flow of information and interaction within the field is largely channeled through these central clusters, establishing these core authors as the key influential figures who drive the research agenda.

3.3 Analysis of countries with the most publications.

Figure 3 presents information on the global distribution of research related to car headlights, driving safety, and comfort. This figure highlights not only the leading countries in this field but also the collaborative networks driving innovation in headlight technologies.

Countries are ranked according to the number of published documents, citations received, and total link strength. The United States leads in the number of documents and citations, indicating a substantial research presence. China follows with 160 documents and 1173 citations, demonstrating its growing contribution to the field. Germany and Taiwan also emerge as significant contributors. The presence of countries like India, South

Korea, and Japan further emphasizes the global nature of this research area. It is important to note that "total link strength" is likely a composite measure, possibly derived from co-authorship or citation patterns, reflecting interconnectedness among research activities across countries.

These findings demonstrate the global nature of research on car headlights and their connection to driving safety and comfort. The prominence of certain countries underscores their leadership in this area, while the collaborative links highlight the importance of international partnerships in driving innovation and addressing shared challenges related to road safety. Further investigation into the specific research areas within each country and the nature of collaborative projects could yield more nuanced insights.

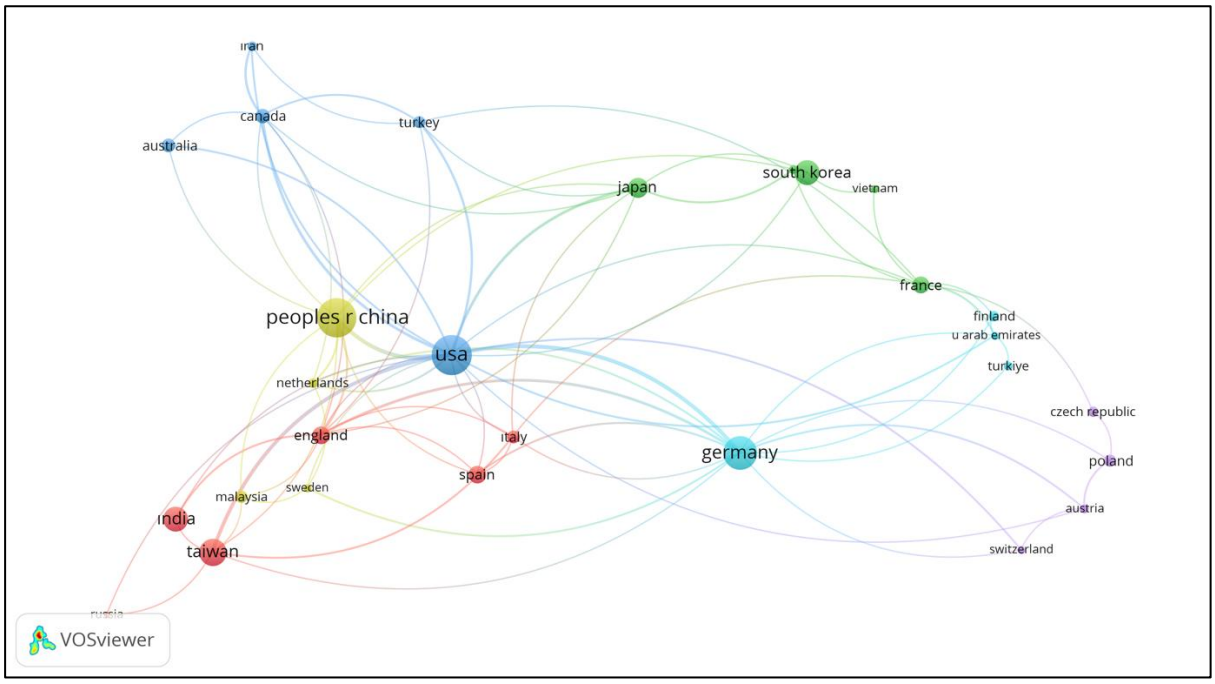

Figure 3. Analysis of countries with the most publications.

Shown in Figure 3 the network map clearly demonstrates that the USA and Germany stand out as the largest nodes in the research field, positioning these two countries as the central actors of the global collaboration network. The USA, in particular, forms the most intensive collaboration hub in the network due to its robust connections with both China (Peoples R China) and various European and Asian countries.

Despite having a large research output, China's collaboration structures are often positioned closer to the USA; whereas Asian countries like Japan and South Korea form a distinct

collaboration cluster, establishing strong ties amongst themselves and with Germany. Finally, countries such as India and Taiwan in the bottom left of the map form more localized collaboration clusters, primarily limited to their own regions and specific European partners like the UK/England and Spain.

3.4. Analysis of author citation networks and ınfluence

The analysis of author citation networks offers valuable insights into the structure and dynamics of the research landscape pertaining to car headlights, driving safety, and comfort. This examination reveals key influencers, collaborative patterns, and the overall knowledge flow within the field.

Figure 4 presents the most cited researchers, considering 139 researchers with at least two publications and one citation. The most cited researcher is Andreas Herrmann (330). Following Herrmann, in descending order of citation count, are Yuxiang Sun, Bing-fei Wu (253), Ming Liu (252), Murat Uysal (252), Jan R. Landwehr (248), Yen-lin Chen (239), Hao-yu Huang (178), and Yee Mun Lee (174). The figure indicates that the top-performing researchers are primarily affiliated with universities in Germany, China, Taiwan, and Turkey.

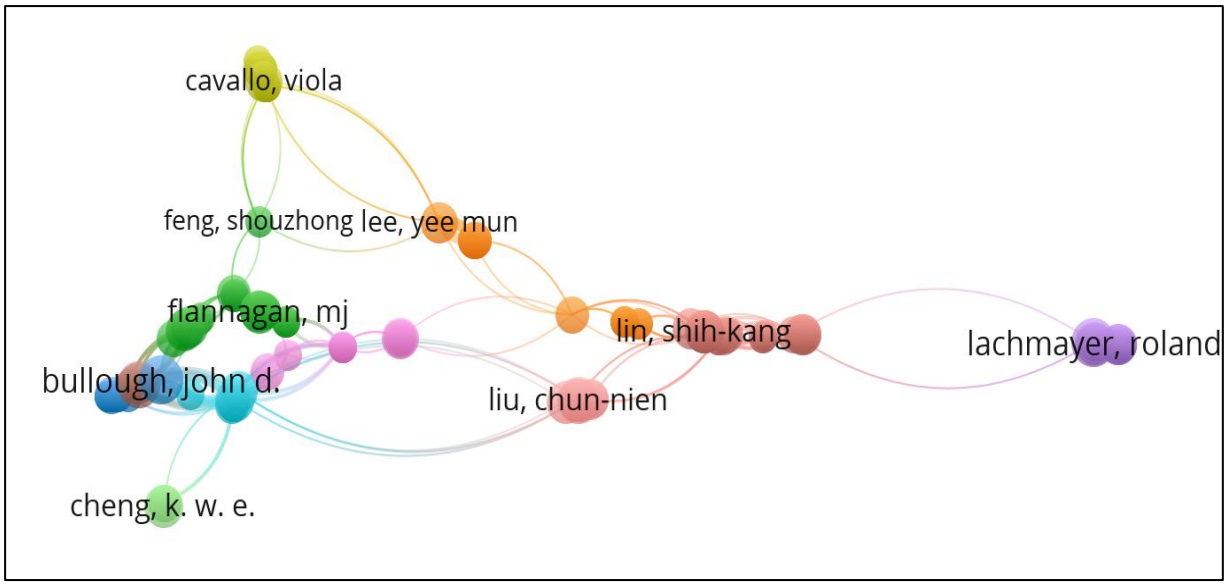

Figure 4. Analysis of Author Citation Networks and Influence

The visualization of these citation connections as a network graph further illuminates the relationships between researchers. Authors are represented as nodes, with the connections between them representing citations. The density of these connections, often depicted by the thickness of the connecting lines, reflects the frequency of citation between authors. This graphical representation can reveal clusters of interconnected researchers, potentially signifying collaborative groups or areas of focused research activity. Such collaborative networks can be instrumental in advancing specific technologies like adaptive driving beams (Fechtner et al., 2019) or addressing critical issues such as glare and driver perception. (Mehri et al., 2017; Weaver & DeLucia, 2022) Further analysis of these clusters might uncover specialized research domains within the broader field.

This combined quantitative and visual analysis provides a comprehensive understanding of the intellectual landscape. By examining citation patterns, we gain insights into not only the most influential researchers but also the potential for future collaboration and the evolution of research themes over time. The directionality of citations, from older to newer works, can further elucidate the trajectory of research within this domain. Furthermore, this approach can help identify emerging research trends and potential gaps in the existing literature.

3.5 Most cited publications

Figure 5 shows the most cited publications. Out of a total of 953 publications analyzed, 664 publications with at least one citation were found, and 231 of these publications were taken into consideration. Examining the figure, it can be seen that the most cited publication is that of Lin(2009, 325 citation). This publication is followed by Quddus(2002, 278 citation), Sun(2019, 250 citation), Landwehr(2011, 212 citation), O'Malley(2010, 164 citiation), Chen(2011, 142 citation), Zhou(2007, 140 citation), Uysal(2015, 132 citation), Unzueta(2012, 119 citation), and Jermakian(2011, 113 citation), in order.

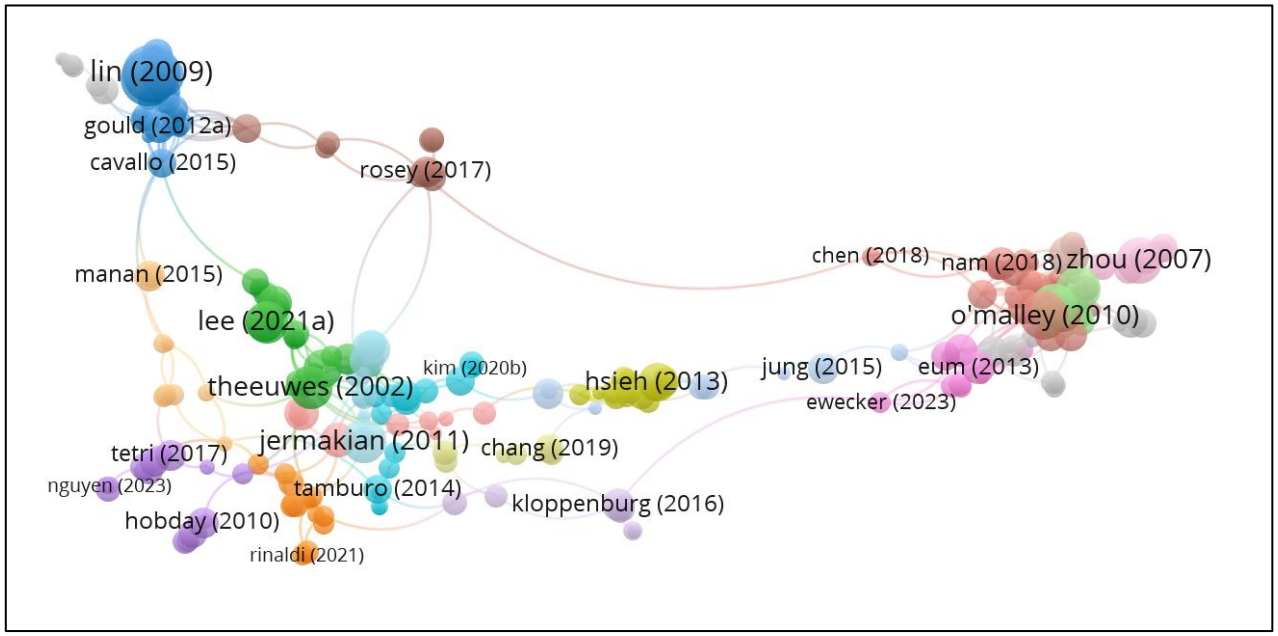

Figure 5 Most cited publications

There are important indicators that show the quality and impact of publications. The citation counts of publications demonstrate their level of contribution and effectiveness in the field. It is known that publications with high citation counts are more prestigious and of higher quality (González-Brignardello et al., 2023) (Redner, 1998).

In addition, the multi-authorship of publications is also a remarkable finding. It has been observed that multi-authored publications have higher citation counts (Kosmulski, 2017; Redner, 1998).

It is observed that studies published especially in 2018-2019 have become quite popular. This is due to the acceleration of scientific publishing and the increase in studies conducted in this field, which explains the increase in citation counts during this period."

3.6 Distribution of publications over the years

Figure 6 shows the distribution of publications related to vehicle headlights, driving safety, and comfort over the years. This temporal analysis provides important insights into research trends and the increase in interest in this area over time. A noteworthy observation is the recent increase in the number of publications. The years 2021, 2022, and 2024 account for a significant portion of the total publications. This surge may reflect an increasing focus on advanced driver assistance systems, including smart headlight technologies such as adaptive driving beams and the integration of sensor-based equipment. The development and application of LED and other innovative lighting systems also contribute to this trend.

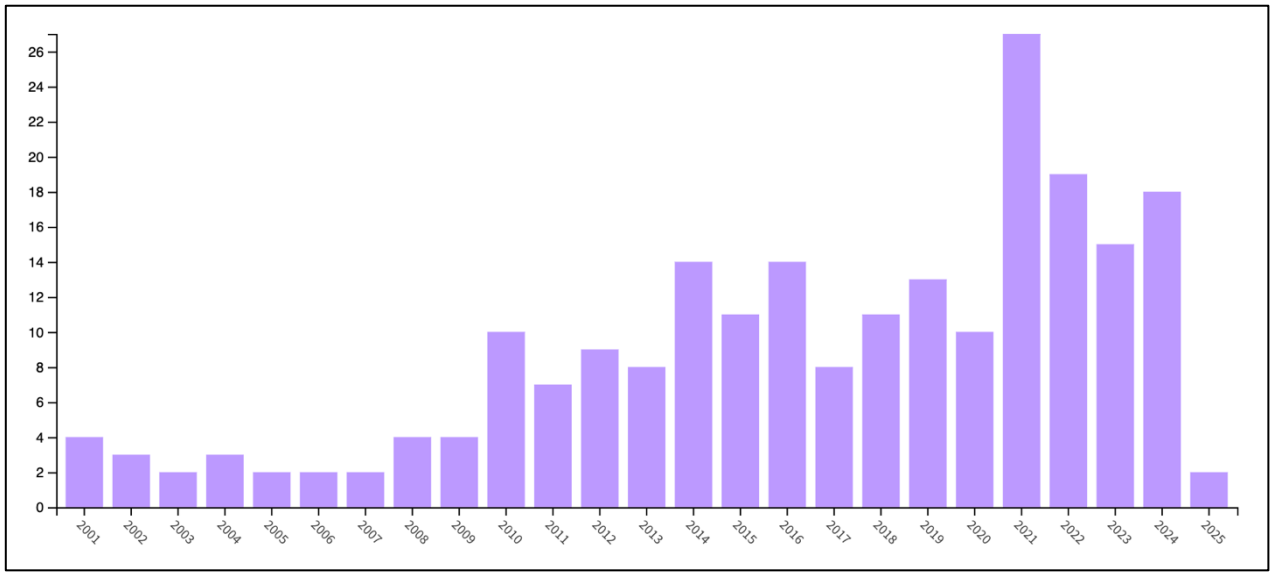

Figure 6 Distribution of publications over the years

Although there has been a noticeable concentration of publications in recent years, the data also reveals steady research activity dating back to the early 2000s. While the number of publications in the years between 2001 and 2019 is generally lower compared to the recent increase, these represent foundational research that paved the way for current advancements. Three records with missing publication year data were excluded from the analysis, as they represent a small fraction of the total dataset.

This temporal distribution analysis demonstrates a growing research interest in vehicle headlights, particularly focusing on their roles in enhancing driving safety and comfort. The increased number of publications in recent years aligns with the automotive industry's focus on innovative lighting technologies and the integration of smart functions into vehicles. This trend indicates that research in this area will continue to expand, driven by ongoing technological developments and the pursuit of safer and more comfortable driving experiences.

4. DISCUSSION AND CONCLUSIONS

The analysis of research trends in vehicle headlights, driving safety, and comfort reveals several key insights. The increasing number of publications in recent years, particularly in 2021, 2022, and 2024, indicates a growing focus on this area. This surge likely reflects the automotive industry's emphasis on advanced driver assistance systems and innovative lighting technologies, such as adaptive driving beams and LED systems.

The prominence of certain countries, such as Germany, China, Taiwan and Turkey, in the research landscape underscores their leadership in this field [Figures 3, 4]. Collaborative links between researchers across different countries highlight the importance of international partnerships in driving innovation and addressing shared challenges related to road safety.

Furthermore, the analysis of author citation networks identifies key influencers, such as Andreas Herrmann, and collaborative patterns within the field [Figure 4]. These

networks play a crucial role in advancing specific technologies and addressing critical issues like glare and driver perception.

The analysis of publications also reveals that multi-authored publications have higher citation counts, demonstrating the value of collaboration and diverse perspectives in research. Moreover, studies published in 2018-2019 have gained considerable popularity, likely due to the acceleration of scientific publishing and increased research activity in this domain.

While recent years have witnessed a concentration of publications, steady research activity has been ongoing since the early 2000s. These earlier studies provide the foundational research that paved the way for current advancements.

In conclusion, this analysis demonstrates a growing research interest in vehicle headlights and their impact on driving safety and comfort. The increasing number of publications, the prominence of certain countries and researchers, and the collaborative networks within the field all point to the continued expansion of research in this area. This expansion is driven by ongoing technological developments and the pursuit of safer and more comfortable driving experiences. Further research could explore specific research areas within each country, the nature of collaborative projects, and emerging trends in lighting technologies.

The research conducted in this study has shown the importance of the colors of headlights for drivers, especially oncoming drivers, and that there are very few publications on the issues of glare caused by car headlights and, in particular, a clear need for further studies on these subjects. Further research into the color properties of headlights and their effects on drivers, especially regarding glare, holds significant potential for improving road safety and driving comfort. Understanding how different headlight colors affect visibility and perceived glare could lead to the development of optimized lighting systems that minimize discomfort for oncoming drivers while maximizing visibility for the vehicle operator. This could reduce accidents caused by glare-induced temporary blindness or impaired vision, particularly at night or in adverse weather conditions. Moreover, studying these factors could inform the creation of more ergonomic and user-friendly headlight designs, enhancing the overall driving experience and promoting safer roadways for all users.

Based on a bibliometric analysis, automotive manufacturers should concentrate on several key strategic areas to improve driving safety and comfort. These include accelerating the development and production of smart and adaptive lighting technologies, such as Smart Headlamp Systems and Adaptive Driving Beams, which have seen increased research focus recently. A critical aspect of this development is mitigating glare from high-luminosity LED and HID systems, requiring further research into the color properties of headlights and their impact on drivers to create systems that balance visibility with reduced discomfort for others. Furthermore, manufacturers should integrate sustainability and life cycle thinking into their designs, ensuring a balance between headlamp performance, environmental impact, and ecological considerations. Ergonomic and vehicle-type-specific designs are also crucial, focusing on user-friendliness and adapting headlamp features to different vehicle types and

driving scenarios. Finally, strengthening academic and international collaboration, potentially by partnering with key influential players identified in research networks, and leveraging methodologies like digital twins to optimize performance through accurate simulations, are recommended for accelerating innovation in automotive lighting.

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THE NOVEL HEWMA EXPONENTIAL TYPE MEAN ESTIMATOR UNDER RANKED SET SAMPLING

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Abstract: This study introduces a novel HEWMA-based exponential estimator for Ranked Set Sampling (RSS). The proposed estimator integrates HEWMA control chart statistics with the exponential ratio estimator to enhance efficiency. By incorporating control chart statistics, memory-type estimators improve estimation accuracy by utilizing not only the mean of the current sample but also historical means, if available. This approach enables using time-dependent repeated survey data or data collected from the same population at different time points. Given that the only existing estimator for the RSS method in the literature is the ratio estimator using EWMA, the proposed estimator offers a more efficient alternative. Its efficiency is evaluated through simulation studies using synthetic datasets with varying correlation coefficients to simulate diverse scenarios, as well as an empirical study employing real-world data with a distinct structure. The results demonstrate that incorporating at least one old sample mean value enhances efficiency. Additionally, the estimator's effectiveness improves as correlation and the number of old means used (T) increase. The selection of HEWMA weight parameters is crucial, depending on sample size and correlation. The proposed estimator performs optimally at low to medium correlation levels in the simulation studies and consistently outperforms alternatives in the real data analysis.

Keywords: Ranked set sampling, HEWMA, Memory type, Estimator, Simulation.

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1. INTRODUCTION

Ranked Set Sampling (RSS), originally proposed by McIntyre (1952), offers a more efficient alternative to Simple Random Sampling (SRS), especially in scenarios where measuring the study variable is costly, time-consuming, or destructive. RSS improves estimator precision by incorporating rankings before actual measurements, thus utilizing available information more effectively. In parallel, memory-type estimators like the Exponentially Weighted Moving Average (EWMA) chart by Roberts et al. (1959) and its extension, the Hybrid Exponentially Weighted Moving Average (HEWMA) chart introduced by Haq (2013), are widely used for monitoring processes that evolve over time. These methods integrate historical and recent data,

giving more weight to recent observations while still considering past trends. HEWMA enhances its flexibility by allowing a dynamic weighting scheme to capture shifts in the underlying process better. Arslan et al. (2023) demonstrated that the hybrid HEWMA control chart is more sensitive than existing control charts, including the classical EWMA, in detecting early shifts in process parameters. This feature makes HEWMA particularly suitable in the RSS context, where the efficient use of auxiliary and temporal information is crucial. Combining RSS with HEWMA can further improve estimation accuracy.

Aslam et al. (2020) introduced memory-type ratio and product-type mean estimators utilizing EWMA in stratified and rank-based sampling techniques. Shahzad et al. (2022) proposed EWMA-type memory-type estimators in two-stage sampling. Alomaie and Iftikhar (2024) introduced calibrated EWMA estimators for time-dependent survey data to the literature with various applications. Aslam et al. (2024) introduced a novel memory-based ratio estimator for survey sampling, whereas Kumar and Bhushan (2025) proposed a logarithmic memory-type estimator for time-dependent studies. Kumar et al. (2024) presented a class of memory-type general variance estimators under SRS. Singh et al. (2024) enhanced the accuracy of memory-type mean estimators, and Sharma et al. (2024) designed procedures for the EWMA mean estimator in time-dependent studies. Recently, Kumari et al. (2025) proposed a memory-type estimator using two auxiliary variables, and Koçyiğit (2025) introduced a new and effective HEWMA-type estimator under SRS. This method has been frequently studied and developed differently in recent years (Singh et al. 2021, Bhushan et al. 2022, Shahzad et al. 2022, Yadav et al. 2023, Aslam et al. 2023, Alomair and Shahzad 2023, Qureshi 2024, Tariq et al. 2024, Kumar et al. 2024). However, no study has proposed a estimator using HEWMA under RSS in the literature. Studies have shown that both the RSS method and HEWMA control chart, proposed as alternatives, produce more effective results than the SRS method and EWMA control chart.

This study evaluates the effectiveness of the HEWMA exponential type estimator proposed for the RSS method, comparing it to other estimators in the literature through simulation studies using synthetic datasets and real data from Türkiye. As a result, a new estimator for the RSS method is developed, improving estimation accuracy by integrating historical sample means.

2. MEAN ESTIMATORS UNDER RSS

Cingi and Kadılar (2009) generally classified the mean estimators as basic, ratio/product and regression type. However, these estimators have expanded with the development of technology and the expansion of literature, including exponential type, logarithmic type estimators, estimator families, etc. Aslam et al. (2020) included memory-type estimators among these estimator groups. This section presents the basic mean, ratio, regression type, and memory-type mean estimators for RSS, followed by introducing the new proposed estimator.

2.1. Estimators in the literature

In RSS, the mean estimation is primarily performed using the formula in Equation (1), where Y represents the study variable of interest and X serves as the auxiliary variable.

$$\mu_{RSS} = \sum_{j=1}^{c}\sum_{i=1}^{s} y_{(i;j)} \Big/ sc \tag{1}$$

Here, s is the RSS set size, and c is the number of repetitions/ cycles. This estimator does not use any auxiliary variable information. Equation (2) presents the ratio estimator in RSS.

$$\mu_2 = \left(\mu_{RSS} / \bar{x}_{SKÖ}\right)\overline{X}, \tag{2}$$

where $\bar{x}_{RSS} = \sum_{j=1}^{c}\sum_{i=1}^{s} x_{(i:j)} \Big/ sc$ is the sample mean of the auxiliary variable drawn with RSS. RSS's exponential ratio and regression type estimators are as in Equations (3) and (4), respectively.

$$\mu_3 = \mu_{RSS} \exp\left[\left(\overline{X} - \bar{x}_{RSS}\right) \Big/ \left(\overline{X} + \bar{x}_{RSS}\right)\right] \tag{3}$$

$$\mu_4 = \mu_{RSS} + b\left(\overline{X} - \bar{x}_{RSS}\right) \tag{4}$$

In Equation (4), b denotes the regression coefficient, which can be estimated using $\hat{b} = \rho\left(s_y / \bar{y}\right)\left(s_x / \bar{x}\right)$, where s_y and s_x are the standard deviations of Y and X samples, respectively. ρ is the correlation coefficient between X and Y. In Equations (2), (3), and (4), $\overline{X}$ is the population mean of the auxiliary variable.

The following formula presents the EWMA-based memory-type ratio estimator in RSS proposed by Aslam et al. (2020).

$$\mu_{5T} = \left(\mu_{EWMAY} / \bar{x}_{EWMAX}\right)\overline{X} \tag{5}$$

Here, $\mu_{EWMAY(T)} = \alpha\mu_{RSS(T)} + (1-\alpha)\mu_{EWMAY(T-1)}$ and $\mu_{EWMAX(T)} = \alpha\bar{x}_{RSS(T)} + (1-\alpha)\mu_{EWMAX(T-1)}$ are the EWMA statistics for Y and X. α is the weight parameter of the EWMA statistic and chosen in $0 < \alpha \leq 1$.

2.2. Proposed estimator

The following formulas calculate the HEWMA statistics for variables Y and X, respectively:

$$\mu_{HEWMAY(T)} = (1-\beta)\mu_{HEWMAY(T-1)} + \beta\mu_{EWMAY(T)} \tag{6}$$

$$\mu_{HEWMAX(T)} = (1-\beta)\mu_{HEWMAX(T-1)} + \beta\mu_{EWMAX(T)} \tag{7}$$

In this case, β is the weight parameter of the HEWMA statistic, and, similar to the EWMA weight parameter α, it should be chosen from the range $0 < \beta \leq 1$. Both α and β determine the weight given to old mean(s) in the estimation. When T = 1, only the current sample data is used, and no old mean are included. According to Koçyiğit (2025), the initial value of the EWMA statistic should be the oldest mean value.

Inspired by the estimators from Aslam et al. (2020) and Koçyiğit (2025), the HEWMA type exponential proportional estimator is proposed as in Equation (8):

$$\mu_{PROT} = \mu_{HEWMAY(T)}\, exp\left[\frac{\overline{X} - \mu_{HEWMAX(T)}}{\overline{X} + \mu_{HEWMAX(T)}}\right] \qquad (8)$$

3. SIMULATION STUDY

The simulation study was conducted using the R program. The populations were derived from the bivariate normal distribution with ρ_{xy} = 0.6, 0.7, and 0.8, with N(3,1) random parameters and a size of N = 3600. For RSS, we consider the set size as s = 3, 4, and 5 and the number of cycles as c = 1, 2, and 3. For EWMA and HEWMA statistics, we used T = 2, α = 0.1, 0.3, 0.5, 0.7, and 0.9, and β = 0.3, 0.5, 0.7, and 0.9. Koçyiğit (2025) emphasized that the β coefficient should be selected higher than 0.5, but since that study was carried out under SRS, we also tried β = 0.3 for RSS in this simulation study. The simulation draws 100,000 samples from the populations defined using RSS and calculates the corresponding estimator values. The flowchart in Figure 1 summarizes the process for calculating the memory type estimators in simulation. In both EWMA and HEWMA, only sample means were utilized.

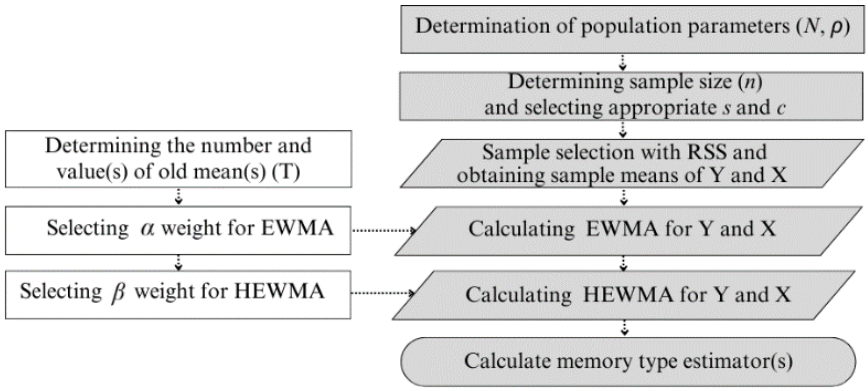

Figure 1. Flowchart of the estimation process using memory type estimators under RSS

Equation (9) calculated the estimators' mean square error (MSE) values , and Equation (10) calculated the relative Efficiency (RE) values . The results are given in Tables 1, 2, and 3. The highest RE value in each s, c combination is written in bold.

$$MSE\left(\mu_j\right) = \frac{1}{100000}\sum_{i=1}^{100000}\left(\mu_{j\_i} - \overline{Y}\right)^2, \quad j = RSS, 2, 3, 4, 5T, PROT \qquad (9)$$

$$RE_v = \frac{MSE\left(\mu_{RSS}\right)}{MSE\left(\mu_v\right)}, v = 2, 3, 4, 5T, PROT \qquad (10)$$

Table 1 shows that the proposed μ_{PROT} estimator produces the most effective results for each s, c combination. The estimator achieves its highest RE value for the low correlation case, (approximately 2.59) with α=0.3, β=0.5, s=3, c=3). At a correlation of 0.7, the estimator reaches the maximum RE value of roughly 2.91 for α=0.1, β=0.5, s=3, c=3.

As shown in Table 2, an increase in correlation leads to a rise in the RE value of the proposed estimator. However, at 0.8 correlation, the best estimator is μ_{5T}. The highest RE value of μ_{5T} is calculated as approximately 3.64 in the case of α=0.5, s= 3, c=3. The highest RE value of the proposed estimator (Approximately 3.42) is obtained from the case of α=0.1, β =0.5, s= 3, c=3.

The simulation study results indicate that memory-type estimators (μ_{5T} and μ_{PROT}) outperform simple, ratio, and regression-type estimators across all conditions. The efficiency of the estimators is significantly influenced by the sample size and selected weight parameters. The proposed estimator does not yield the best result when β=0.3.

Table 1. Simulation results for different values of α, β, s and c when ρ_{xy} =0.6 and 0.7

T=2 N=3600 *N(3,1)* ρ_{xy} =0.6		*s*	*3*	*4*	*5*	*3*	*4*	*5*	*3*	*4*	*5*
		c	*1*	*1*	*1*	*2*	*2*	*2*	*3*	*3*	*3*
		RE_2	1.03827	1.05589	1.06075	1.09609	1.08367	1.08518	1.10936	1.09328	1.08272
		RE_3	1.25847	1.21574	1.18709	1.27761	1.22552	1.19435	1.28021	1.22719	1.19083
		RE_4	1.28753	1.23531	1.17885	1.22488	1.20972	1.20183	1.28686	1.23867	1.19462
α=0.1		RE_{5T}	1.30157	1.30544	1.30144	1.32685	1.31298	1.34863	1.35661	1.33690	1.32216
	β =0.3	RE_{PROT}	2.21469	2.10293	2.04153	2.20185	2.09172	2.09546	2.22210	2.12243	2.05426
	β =0.5	RE_{PROT}	**2.56756**	2.43533	2.36323	**2.56853**	2.45429	2.40789	2.57041	2.45682	2.38237
	β =0.7	RE_{PROT}	2.17749	2.10191	2.05036	2.20117	2.12996	2.07416	2.20654	2.12532	2.04804
	β =0.9	RE_{PROT}	1.54458	1.49053	1.44977	1.55480	1.49701	1.45651	1.55909	1.49974	1.45835
α=0.3		RE_{5T}	1.87045	1.85555	1.83616	1.90366	1.88491	1.86952	1.92829	1.92067	1.87710
	β =0.3	RE_{PROT}	2.19198	2.10680	2.03030	2.19716	2.10755	2.05241	2.21036	2.13958	2.05861
	β =0.5	RE_{PROT}	2.54347	2.45101	2.38094	2.54243	2.40403	2.40403	**2.57889**	**2.47459**	**2.40235**
	β =0.7	RE_{5T}	1.87116	1.85823	1.85992	1.91629	1.89130	1.88297	1.93606	1.91757	1.87419
	β =0.9	RE_{PROT}	1.54298	1.48893	1.45378	1.55632	1.49288	1.45563	1.55607	1.49787	1.45944
α=0.5		RE_{5T}	2.17735	2.18594	2.16045	2.21952	2.17630	2.18858	2.24010	2.22500	2.20119
	β =0.3	RE_{PROT}	2.19621	2.12283	2.05344	2.19055	2.10245	2.06332	2.19892	2.14335	2.08463
	β =0.5	RE_{PROT}	2.53754	**2.46909**	2.34902	2.55542	2.44093	**2.41278**	2.57101	2.45728	2.39840
	β =0.7	RE_{PROT}	2.18246	2.08871	2.05187	2.19277	2.12178	2.05250	2.22485	2.11155	2.04398
	β =0.9	RE_{PROT}	1.54087	1.48638	1.44718	1.54645	1.49748	1.45324	1.55940	1.50007	1.45801
α=0.7		RE_{5T}	1.86006	1.87156	1.85224	1.90002	1.90263	1.87861	1.92958	1.89252	1.85782
	β =0.3	RE_{PROT}	2.17519	2.12388	2.03756	2.18077	2.13098	2.04782	2.21263	2.11167	2.05253
	β =0.5	RE_{PROT}	2.54876	2.46418	2.37546	2.55920	**2.45890**	2.38594	2.57237	2.46256	2.37859
	β =0.7	RE_{PROT}	2.18511	2.11256	2.03706	2.19553	2.11828	2.06539	2.20901	2.13174	2.05784
	β =0.9	RE_{PROT}	1.53587	1.48573	1.44864	1.54803	1.49401	1.45977	1.56293	1.49580	1.45798
α=0.9		RE_{5T}	1.28819	1.30350	1.29526	1.34522	1.32956	1.32866	1.35068	1.34160	1.33102
	β =0.3	RE_{PROT}	2.19947	2.10816	2.04508	2.20933	2.10412	2.05324	2.19172	2.12957	2.09137
	β =0.5	RE_{PROT}	2.52177	2.45059	**2.38297**	2.54296	2.45711	2.40780	2.57742	2.45623	2.39420
	β =0.7	RE_{PROT}	2.18838	2.10840	2.04936	2.19557	2.11775	2.06097	2.20296	2.12245	2.06982
	β =0.9	RE_{PROT}	1.54127	1.48337	1.44640	1.55225	1.48995	1.45576	1.55453	1.50515	1.45537
ρ_{xy} =0.7		RE_2	1.28524	1.26409	1.22942	1.33026	1.28897	1.24427	1.35187	1.30136	1.25375
		RE_3	1.42334	1.35649	1.30386	1.43916	1.36387	1.30863	1.44499	1.36879	1.31182
		RE_4	0.60014	1.27526	1.28698	1.41231	1.37369	1.32275	1.46180	1.39479	1.33560
α=0.1		RE_{5T}	1.58427	1.54658	1.52623	1.63093	1.59357	1.51809	1.66136	1.59525	1.52967
	β =0.3	RE_{PROT}	2.47321	2.34226	2.27931	2.46763	2.36939	2.24809	2.50271	2.37281	2.26240
	β =0.5	RE_{PROT}	2.88072	2.71107	2.63621	2.88851	2.74342	2.63976	**2.91038**	2.74050	2.63173
	β =0.7	RE_{PROT}	2.47092	2.35134	2.26681	2.50079	2.35965	2.27702	2.51112	2.36703	2.26626
	β =0.9	RE_{PROT}	1.74579	1.66187	1.60074	1.75841	1.66942	1.60817	1.76944	1.66421	1.60211
α=0.3		RE_{5T}	2.30083	2.24105	2.15997	2.33875	2.25400	2.16533	2.33605	2.24250	2.17058
	β =0.3	RE_{PROT}	2.48145	2.37561	2.26321	2.50040	2.35665	2.26556	2.48271	2.34634	2.26420
	β =0.5	RE_{PROT}	**2.88967**	2.73033	2.62868	2.89617	2.72913	2.64257	2.89261	2.75599	2.61064
	β =0.7	RE_{PROT}	2.47138	2.34616	2.25145	2.48208	2.35887	2.27150	2.49077	2.37263	2.26508
	β =0.9	RE_{PROT}	1.74693	1.65682	1.59410	1.75640	1.67228	1.60721	1.76531	1.67352	1.60265
α=0.5		RE_{5T}	2.69737	2.58348	2.49598	2.74704	2.61925	2.50818	2.74215	2.62053	2.52764
	β =0.3	RE_{PROT}	2.49311	2.34712	2.25342	2.51752	2.36419	2.24776	2.49824	2.36048	2.26732

	β =0.5	RE_{PROT}	2.85309	**2.73925**	2.64020	2.88351	2.73319	2.63591	2.91015	2.73432	**2.63693**
	β =0.7	RE_{PROT}	2.47308	2.35013	2.27472	2.49945	2.35813	2.26392	2.49802	2.36501	2.27307
	β =0.9	RE_{PROT}	1.74299	1.65974	1.59630	1.75930	1.66637	1.59996	1.76675	1.66896	1.60455
		RE_{5T}	2.27744	2.21252	2.16571	2.32792	2.24118	2.18926	2.36342	2.25382	2.18927
	β =0.3	RE_{PROT}	2.48019	2.35108	2.27082	2.48714	2.35460	2.28343	2.50964	2.37472	2.27329
α=0.7	β =0.5	RE_{PROT}	2.87813	2.73222	**2.64701**	2.90152	**2.76709**	**2.64577**	2.88916	**2.76265**	2.62201
	β =0.7	RE_{PROT}	2.46954	2.36128	2.26442	2.48437	2.35985	2.26196	2.49180	2.35276	2.27840
	β =0.9	RE_{PROT}	1.74608	1.66120	1.60053	1.76175	1.66982	1.59997	1.76455	1.67369	1.60522
		RE_{5T}	1.57434	1.54638	1.51720	1.66016	1.59715	1.53764	1.63648	1.59688	1.54721
	β =0.3	RE_{PROT}	2.46035	2.34457	2.27855	2.51528	2.38194	2.26781	2.49001	2.36282	2.28444
α=0.9	β =0.5	RE_{PROT}	2.88813	2.72990	2.64183	**2.90448**	2.73948	2.63637	2.90833	2.75378	2.60945
	β =0.7	RE_{PROT}	2.46711	2.36513	2.25458	2.50194	2.36655	2.26593	2.48736	2.36286	2.27238
	β =0.9	RE_{PROT}	1.75000	1.66460	1.59557	1.76381	1.66726	1.59706	1.76706	1.67426	1.60151

Table 2. Simulation results for different values of α, β, s and c when ρ_{xy} =0.8

T=2 N=3600 *N(3,1)* ρ_{xy} =0.8		*s*	*3*	*4*	*5*	*3*	*4*	*5*	*3*	*4*	*5*
		c	*1*	*1*	*1*	*2*	*2*	*2*	*3*	*3*	*3*
		RE_2	1.71283	1.60795	1.53905	1.76213	1.63640	1.55552	1.79236	1.65120	1.58990
		RE_3	1.67328	1.56290	1.49231	1.67976	1.57294	1.49022	1.69276	1.57388	1.50565
		RE_4	0.71195	1.43372	1.52706	1.75356	1.67324	1.59336	1.84294	1.70553	1.62942
		RE_{5T}	2.13754	1.97525	1.88501	2.18123	1.99022	1.89744	2.18478	2.03953	1.93649
	β =0.3	RE_{PROT}	2.94202	2.70619	2.55047	2.92495	2.69915	2.57440	2.92997	2.72245	2.61241
α=0.1	β =0.5	RE_{PROT}	3.36626	3.17044	2.99930	3.39494	3.17055	2.99719	3.42350	3.12073	2.99669
	β =0.7	RE_{PROT}	2.89584	2.70702	2.58512	2.94066	2.74096	2.58620	2.93127	2.73304	2.58188
	β =0.9	RE_{PROT}	2.04247	1.91750	1.82074	2.05255	1.92256	1.81501	2.06474	1.93335	1.82418
		RE_{5T}	3.10842	2.852734	2.70097	3.13675	2.84618	2.72654	3.12179	2.87843	2.73210
	β =0.3	RE_{PROT}	2.93512	2.722804	2.58991	2.94951	2.71453	2.60093	2.93741	2.72597	2.58702
α=0.3	β =0.5	RE_{PROT}	3.38653	3.14022	2.98365	3.39932	3.16130	2.98032	3.40011	3.18136	3.01476
	β =0.7	RE_{PROT}	2.89534	2.70602	2.58168	2.91648	2.72416	2.59685	2.92061	2.72599	2.57661
	β =0.9	RE_{PROT}	2.05459	1.91103	1.81754	2.06473	1.91969	1.82450	2.06604	1.92622	1.82251
		RE_{5T}	**3.56380**	**3.31011**	**3.09262**	**3.62782**	**3.45203**	**3.13156**	**3.63738**	**3.38155**	**3.14342**
	β =0.3	RE_{PROT}	2.91470	2.72525	2.54972	2.93477	2.74195	2.57426	2.93844	2.75333	2.58317
α=0.5	β =0.5	RE_{PROT}	3.36035	3.18900	2.98337	3.37095	3.14516	2.98391	3.40109	3.14007	3.01310
	β =0.7	RE_{PROT}	2.91205	2.71697	2.57419	2.90798	2.69810	2.58530	2.92061	2.74156	2.58744
	β =0.9	RE_{PROT}	2.05261	1.91254	1.81332	2.06334	1.93418	1.83043	2.06785	1.92910	1.82562
		RE_{5T}	3.05964	2.85001	2.67018	3.10072	2.89379	2.69481	3.09449	2.88060	2.71351
	β =0.3	RE_{PROT}	2.92198	2.72438	2.56504	2.91465	2.73783	2.59153	2.89156	2.76326	2.58293
α=0.7	β =0.5	RE_{PROT}	3.37407	3.15686	3.00465	3.39558	3.17473	2.99640	3.40294	3.14645	2.99577
	β =0.7	RE_{PROT}	2.89909	2.70666	2.58938	2.92225	2.71378	2.58114	2.90881	2.73945	2.57079
	β =0.9	RE_{PROT}	2.04912	1.91097	1.81518	2.06123	1.91906	1.82088	2.07428	1.92487	1.83668
		RE_{5T}	2.11918	1.98502	1.90494	2.19624	2.01012	1.90776	2.18161	2.03832	1.90143
	β =0.3	RE_{PROT}	2.87322	2.73399	2.57816	2.94079	2.69731	2.57410	2.91609	2.72483	2.56854
α=0.9	β =0.5	RE_{PROT}	3.38836	3.16588	2.98610	3.38081	3.18038	3.00487	3.41528	3.17518	3.00461
	β =0.7	RE_{PROT}	2.91836	2.72530	2.57491	2.92054	2.70879	2.57103	2.93332	2.73264	2.58685
	β =0.9	RE_{PROT}	2.05199	1.90913	1.82096	2.06410	1.92280	1.829139	2.07381	1.92644	1.82675

4. REAL DATA

This section uses a dataset compiled from the highway statistics of the provinces in Turkey for the years 2024-2022, provided by TÜİK and the EGM Traffic Department. In this dataset, the variables include traffic accidents with death/injury in 2024 as Y (Y_{2024}) and registered motor vehicles in 2024 as X (X_{2024}). The population parameters are summarized in Table 3. The correlations between reveal strong positive relationships among all variables across the years. X_{2022} shows perfect correlation with both X_{2023} and X_{2024} (≈1.00), and strong correlations with Y_{2022} (0.88), Y_{2023} (0.87), and Y_{2024} (0.91). Similarly, X_{2023} is perfectly correlated with X_{2024} (≈1.00), and also shows high correlations with Y_{2022} (0.91), Y_{2023} (0.89), and Y_{2024} (0.93). X_{2024} maintains strong correlations with Y_{2022} (0.92), Y_{2023} (0.91), and Y_{2024} (0.94). Among the Y variables, Y_{2022} and Y_{2023} are perfectly correlated (≈1.00), and both have a very high correlation with Y_{2024} (0.98). It is noteworthy that, unlike the synthetic data sets derived from the bivariate normal distribution in the simulation study, the real data set is quite skewed and has a higher correlation.

Table 3. Population parameters

Variables	N	Min.	Max.	Mean	Std. Dev.	Skewness	Kurtosis
Y_{2024}	81	102	33622	3134.469	4756.553	3.8753	19.5151
X_{2024}	81	1355	651282	32084.15	76892.09	6.6006	49.2155
Y_{2023}	81	175	25622	2902.111	3888.364	3.3178	13.9347
X_{2023}	81	816	637591	28275.06	74762.91	6.8143	51.7037
Y_{2022}	81	129	22914	2435.321	3425.946	3.5234	15.4720
X_{2022}	81	354	412631	15677.93	47566.93	7.2630	57.0207

For the simulation number 100,000, samples were drawn from the abovementioned population with s = 3, 4, and 5, c = 1, 2, and 3. Based on the results obtained from the simulation study, α, β = 0.5, 0.7, and 0.9 were determined. In addition, it was observed how the effectiveness of the estimators changed when the old means number was increased by taking T = 2 and 3. The variable to be estimated belongs to the year 2024 for each T. In the case of T = 2, the variables belonging to the years 2024 and 2023, and in the case of T = 3, the variables belonging to the years 2024, 2023, and 2022 were included in the EWMA and HEWMA algorithms. All other calculations in this section were carried out similarly to the simulation study in Section 3. Table 4 presents the RE values of the estimators.

Table 4 shows the most efficient estimator, the proposed μ_{PROT} estimator. In the case of T=2, when the sample size is minimal, the estimator gives the best values when s=3, c=1 is selected as α=0.5, and in all other cases, α>0.5, and in all cases, β =0.9 should be chosen. For T=3, α>0.5 and β =0.9 should be selected. The efficiency of the estimator increases as the number of T increases. The highest efficiency values are also seen for T=2 and 3, s=3, c=1, while the max. RE is 10.45350 for T=2, α=0.5 and β =0.9, and the max. RE value of 13.75371 is obtained for T=3, α=0.9, and β =0.9.

Since the year of interest is 2024 and the correlation with previous years decreases as we move further back in history with an increase in T, choosing α=β=0.9 causes the oldest average to receive the lowest weight, while the years closer to the present are given more weight. Including the variables with the highest correlation in the estimator with weight positively impacts the efficiency.

Table 4. Simulation Results for Real Data

		s	*3*	*4*	*5*	*3*	*4*	*5*	*3*	*4*	*5*
		c	*1*	*1*	*1*	*2*	*2*	*2*	*3*	*3*	*3*
		RE_2	4.05980	3.76254	3.34796	3.54771	2.97535	2.50368	3.01664	2.46233	2.01799
		RE_3	4.71821	4.98895	5.18671	5.29068	5.68117	5.96377	5.74144	6.11419	6.32070
		RE_4	0.55629	3.13484	3.56586	3.80105	4.01457	3.93822	4.10733	4.01980	3.64466
T=2											
α=0.5		RE_{5T}	4.38971	3.97931	3.70130	1.25833	1.37386	1.45534	0.93964	0.91893	1.00415
	β =0.5	RE_{PROT}	8.51374	6.67309	5.56744	2.73485	2.86038	2.84855	1.89553	1.98091	2.10372
	β =0.7	RE_{PROT}	9.83821	7.73143	6.69895	3.57461	3.74212	3.71784	2.52595	2.61378	2.73821
	β =0.9	RE_{PROT}	**10.45350**	8.93427	7.83421	4.58751	4.72355	4.73417	3.33558	3.42663	3.57875
α=0.7		RE_{5T}	5.09934	4.65513	4.37873	2.21934	2.25129	2.22947	1.73000	1.60356	1.62076
	β =0.5	RE_{PROT}	9.84340	7.91933	6.75985	3.56202	3.70604	3.69892	2.53200	2.59311	2.72194
	β =0.7	RE_{PROT}	10.38918	9.11879	8.40121	5.06556	5.14851	5.22211	3.71435	3.83801	4.03975
	β =0.9	RE_{PROT}	9.64148	9.13816	8.83723	6.65741	6.78301	6.97192	5.30239	5.53439	5.73087
α=0.9		RE_{5T}	4.90734	4.51157	4.00190	3.56979	3.16447	2.74799	3.01612	2.49698	2.14923
	β =0.5	RE_{PROT}	10.36584	8.90518	7.73983	4.64662	4.67680	4.71657	3.36815	3.45453	3.57188
	β =0.7	RE_{PROT}	9.55911	**9.20972**	**8.85166**	6.65892	6.77114	6.93413	5.32073	5.52574	5.73164
	β =0.9	RE_{PROT}	7.28685	7.42025	7.61141	**7.16181**	**7.49348**	**7.89318**	**6.91536**	**7.27596**	**7.57546**
T=3											
α=0.5		RE_{5T}	3.43619	3.17004	2.93587	1.36932	1.42025	1.43193	1.05777	0.99389	1.02447
	β =0.5	RE_{PROT}	11.24214	8.94697	7.74689	4.33793	4.45208	4.49475	3.03944	3.13275	3.34494
	β =0.7	RE_{PROT}	13.45084	11.41015	10.00778	6.02409	6.08622	6.32640	4.31480	4.37793	4.73140
	β =0.9	RE_{PROT}	13.74341	12.19991	11.29841	7.39763	7.61135	7.74592	5.60554	5.75040	6.19978
α=0.7		RE_{5T}	4.68708	4.41981	4.05342	2.39704	2.33988	2.26811	1.91841	1.71608	1.69744
	β =0.5	RE_{PROT}	13.34960	11.44205	10.14812	5.91176	6.11431	6.31161	4.24942	4.35818	4.79750
	β =0.7	RE_{PROT}	13.31635	12.05169	11.41502	7.72355	8.02707	8.25253	5.90144	6.08667	6.45808
	β =0.9	RE_{PROT}	10.81900	10.44883	10.45433	**8.48030**	8.64490	**9.04991**	7.07788	7.36312	7.86653
α=0.9		RE_{5T}	4.91418	4.48625	4.01227	3.53111	3.13567	2.72548	3.00984	2.46611	2.16603
	β =0.5	RE_{PROT}	**13.75371**	**12.27952**	**11.42045**	7.26702	7.58168	7.80883	5.56629	5.67407	6.18815
	β =0.7	RE_{PROT}	10.72578	10.51414	10.62548	8.47284	**8.77406**	9.00512	7.05950	7.32109	7.76861
	β =0.9	RE_{PROT}	7.23490	7.54251	7.78024	7.47679	7.79107	8.15463	**7.34840**	**7.67025**	**8.13815**

5. CONCLUSIONS

In this study, a new HEWMA type memory exponential ratio estimator for RSS is introduced. Thus, a new alternative that gives more effective results than the only estimator in the literature is obtained.

The simulation studies found that the μ_{PROT} outperformed others at low and medium correlation values, as well as in the entire real data study. As the correlation and the number of old mean(s) used (T) increase, the effectiveness of the proposed estimator increases. The selection of HEWMA weight parameters is essential depending on the sample size and correlation. Like Koçyiğit (2025), it should be selected as $\beta \geq 0.5$.

Future research should focus on integrating the HEWMA control chart statistics, which have been demonstrated to outperform EWMA in certain contexts, with a broader set of estimators under RSS. Comparative simulation studies involving different memory-type estimators, such as adaptive EWMA variants or Bayesian-based memory estimators, could provide deeper insights into their relative efficiency. Additionally, rather than relying on arbitrarily chosen

weight parameters in HEWMA, optimization techniques—such as grid search, cross-validation, or data-driven methods based on mean squared error minimization—should be employed to determine optimal weight values. Potential application areas include quality control in manufacturing, environmental monitoring, and medical studies where measurement costs are high but auxiliary information is available.

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SOFT UNION-LAMBDA PRODUCT OF GROUPS

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Abstract: Soft set theory provides a logically sound and algebraically rich framework for modeling systems characterized by ambiguity, epistemic uncertainty, and parameter-dependent variability. This study introduces the soft union–lambda product, a novel binary operation defined over soft sets whose parameter spaces are endowed with an intrinsic group-theoretic structure. Developed within a rigorously formulated axiomatic framework, the operation is shown to be fully compatible with generalized notions of soft subsethood and soft equality. A thorough algebraic investigation is undertaken to establish the fundamental structural properties of the operation—including closure, associativity, commutativity, idempotency, and its distributivity over other soft set operations—alongside a precise characterization of its behavior concerning the identity, absorbing, null, and absolute soft sets. The results demonstrate that the soft union–lambda product adheres to all algebraic constraints dictated by group-parameterized domains, thereby inducing a consistent and internally cohesive algebraic structure on the universe of soft sets. Beyond its foundational contributions, the proposed operation significantly expands the formal toolkit of soft set theory and sets the stage for the development of a generalized soft group theory. Furthermore, its formal alignment with key relational structures such as soft equality and soft inclusion highlights its potential applicability across a diverse array of analytical contexts, including abstract algebraic modeling, uncertainty-aware classification, and multi-criteria decision analysis. Accordingly, the findings of this study offer both profound theoretical advancements and concrete pathways for practical implementation.

Keywords Soft sets, Soft subsets, Soft equalities, Soft union–lambda product.

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1. INTRODUCTION

Numerous mathematically rigorous frameworks have been developed to address ambiguity, indeterminacy, and uncertainty in diverse domains, including engineering, economics, the social sciences, and medical diagnostics. However, classical paradigms—particularly fuzzy set theory introduced by Zadeh (1965) and probabilistic models—suffer from intrinsic limitations. Fuzzy set theory relies on subjectively defined membership functions, while probabilistic models presuppose well-defined distributions and repeatable experimental conditions, assumptions that are often violated in practical scenarios.

To circumvent these foundational constraints, Molodtsov (1999) proposed soft set theory as a parameter-driven alternative that dispenses with both probability and fuzziness, enabling the treatment of uncertainty in a more flexible and structurally neutral manner. Foundational operations were first introduced by Maji et al. (2003) and were subsequently reinterpreted by Pei and Miao (2005) through an information-theoretic framework, enriching the conceptual depth of the theory. The operational formalism was further extended by Ali et al. (2009), who defined restricted and extended soft operations. A significant body of work followed—contributed by Yang (2008), Feng et al. (2010), Jiang et al. (2010), Ali et al. (2011), Neog and Sut (2011), Fu (2011), Ge and Yang (2011), Singh and Onyeozili (2012a, 2012b, 2012c, 2012d), Zhu and Wen (2013), Şahin and Küçük (2013), Onyeozili and Gwary (2014), Sen (2014), Yang and Yao (2020), Alcantud (2022a,2022b), Ameen and Al Ghour (2023), Santos-García and Alcantud (2023), Akram et al. (2023), and Khan et al. (2025) which advanced the theory by refining its semantics, formulating new algebraic operations, generalizing notions of soft equality, and extending of structures to a soft framework. In more recent developments, researchers such as Eren and Çalışıcı (2019), Stojanović (2021), Sezgin et al. (2023a, 2023b), Sezgin and Aybek (2023), Sezgin and Dağtoros (2023), Sezgin and Demirci (2023), Sezgin and Çalışıcı (2024), Sezgin and Yavuz (2023a, 2023b; 2024), Sezgin and Çağman (2024,2025), Sezgin and Sarıalioğlu (2024a, 2024b), and Sezgin and Şenyiğit (2025) have systematically developed and algebraically formalized a range of novel soft operations, culminating in a robust and internally coherent algebraic architecture for soft set theory with the introduction of some new operations in set theory by Sezgin et al. (2023c).

Parallel advances in the generalization of soft subsethood and soft equality have likewise played a critical role in the algebraic maturation of the theory. Building upon the early work of Pei and Miao (2005), Feng et al. (2010), and Qin and Hong (2010), subsequent refinements by Jun and Yang (2010) and Liu et al. (2012) introduced the notions of J-soft and L-soft equalities. Feng and Li (2013) further classified soft subsets under L-equality and established semigroup structures on associated quotient classes. Broader generalizations—such as g-soft, gf-soft, and T-soft equalities—were elaborated by Abbas et al. (2014, 2017), Al-shami (2019), and Al-shami and El-Shafei (2020), incorporating congruence relations and lattice-theoretic features into the foundational structure of soft algebra. A key milestone in the formal development of the theory was achieved through the axiomatic reformulation proposed by Çağman and Enginoğlu (2010), who eliminated foundational inconsistencies and provided a logically coherent basis for the systematic algebraization of soft set theory. This reformulation paved the way for defining binary soft operations across classical algebraic systems: the soft intersection–union product was extended to rings by Sezer (2012), to semigroups by Sezgin (2016), and groups by Muştuoğlu

et al. (2016). Conversely, the dual soft union–intersection product has been studied in the context of group theory by Kaygısız (2012), semigroup theory by Sezer et al. (2015), and ring theory by Sezgin et al. (2017).

Anchored in this expansive theoretical landscape, the present study introduces a novel binary operation, the soft union–lambda product, defined over soft sets whose parameter domains are endowed with a group-theoretic structure. Formulated within a formally consistent and axiomatically grounded framework, the operation is subjected to a rigorous algebraic analysis, establishing its fundamental properties—closure, associativity, commutativity, idempotency, and distributivity over other soft set operations—while systematically characterizing its behavior concerning the identity, absorbing, null, and absolute soft sets. The operation is shown to preserve compatibility with generalized soft subsethood and soft equality, thereby ensuring its structural integration into the broader algebraic framework of soft set theory. A comparative analysis with previously established soft binary operations highlights the enhanced expressive capacity and structural coherence of the proposed product within layered classifications of soft subsets. By abstracting group-theoretic operations into a parameter-dependent soft setting, this work contributes to the consolidation of a generalized theory of soft groups. It extends the algebraic infrastructure underpinning soft set theory. Furthermore, the proposed framework provides a foundational framework' for future applications in algebraic classification, uncertainty-aware information modeling, and abstract computational paradigms. The remainder of this manuscript is organized as follows: Section 2 presents essential definitions and preliminary results. Section 3 formally introduces the soft union–lambda product and elaborates its algebraic properties. Section 4 synthesizes the core theoretical outcomes and outlines potential research directions pertaining to the algebraic extension and applied deployment of soft set structures under uncertainty.

2. PRELIMINARIES

While Molodtsov's (1999) introduction of soft set theory marked a seminal step toward parameter-driven representations of epistemic uncertainty, its original formulation lacked the algebraic formalism necessary for rigorous theoretical advancement. This foundational deficiency was rectified through the axiomatic restructuring proposed by Çağman and Enginoğlu (2010), who provided a logically sound and algebraically comprehensive framework that supports systematic development. The present work is situated entirely within this refined formal setting, which serves as the theoretical backbone for all ensuing definitions, binary operations, and algebraic constructs. Unless explicitly indicated, every reference to soft sets and their operations in this manuscript adheres to this revised formalism.

Definition 2.1. (Çağman and Enginoğlu, 2010) Let E be a parameter set, U be a universal set, $P(U)$ be the power set of U, and $\mathcal{H} \subseteq E$. Then, the soft set $\digamma_{\mathcal{H}}$ over U is a function such that $\digamma_{\mathcal{H}}: E \to P(U)$, where for all $w \notin \mathcal{H}$, $\digamma_{\mathcal{H}}(w) = \emptyset$. That is,

$$\digamma_{\mathcal{H}} = \{(w, \digamma_{\mathcal{H}}(w)) : w \in E\}$$

From now on, the soft set over U is abbreviated by $\mathcal{SS}$.

Definition 2.2. (Çağman and Enginoğlu, 2010) Let $f_{\mathcal{H}}$ be an $\mathcal{SS}$. If $f_{\mathcal{H}}(w) = \emptyset$ for all $w \in E$, then $f_{\mathcal{H}}$ is called a null SS and indicated by $\emptyset_E$, and if $f_{\mathcal{H}}(w) = U$, for all $w \in E$, then $f_{\mathcal{H}}$ is called an absolute SS and indicated by U_E.

Definition 2.3. (Çağman and Enginoğlu, 2010) Let $f_{\mathcal{H}}$ and $g_{\aleph}$ be two $\mathcal{SS}$s. If $f_{\mathcal{H}}(w) \subseteq g_{\aleph}(w)$, for all $w \in E$, then $f_{\mathcal{H}}$ is a soft subset of $g_{\aleph}$ and indicated by $f_{\mathcal{H}} \widetilde{\subseteq} g_{\aleph}$. If $f_{\mathcal{H}}(w) = g_{\aleph}(w)$, for all $w \in E$, then $f_{\mathcal{H}}$ is called soft equal to $g_{\aleph}$, and denoted by $f_{\mathcal{H}} = g_{\aleph}$.

Definition 2.4. (Çağman and Enginoğlu, 2010) Let $f_{\mathcal{H}}$ be an $\mathcal{SS}$. Then, the complement of $f_{\mathcal{H}}$ denoted by ${f_{\mathcal{H}}}^{c}$, is defined by the soft set ${f_{\mathcal{H}}}^{c}: E \to P(U)$ such that ${f_{\mathcal{H}}}^{c}(e) = U \backslash f_{\mathcal{H}}(e) = \left(f_{\mathcal{H}}(e)\right)'$, for all $e \in E$.

Definition 2.5. (Çağman and Enginoğlu, 2010) Let $f_{\mathcal{H}}$ and $g_{\aleph}$ be two $\mathcal{SS}$s. Then, the intersection of $f_{\mathcal{H}}$ and $g_{\aleph}$ is the $f_{\mathcal{H}} \cap g_{\aleph}$, where $(f_{\mathcal{H}} \widetilde{\cap} g_{\aleph})(w) = f_{\mathcal{H}}(w) \cap g_{\aleph}(w)$, for all $w \in E$.

Definition 2.6. (Sezgin et al., 2025b) Let f_K and $g_{\aleph}$ be two $\mathcal{SS}$s. Then, f_K is called a soft S-subset of $g_{\aleph}$, denoted by $f_K \widetilde{\subseteq}_S g_{\aleph}$ if for all $w \in E$, $f_K(w) = \mathcal{M}$ and $g_{\aleph}(w) = \mathcal{D}$, where $\mathcal{M}$ and $\mathcal{D}$ are two fixed sets and $\mathcal{M} \subseteq \mathcal{D}$. Moreover, two SSs f_K and $g_{\aleph}$ are said to be soft S-equal, denoted by $f_K =_S g_{\aleph}$, if $f_K \widetilde{\subseteq}_S g_{\aleph}$ and $g_{\aleph} \widetilde{\subseteq}_S f_K$.

It is obvious that if $f_K =_S g_{\aleph}$, then f_{K} and $g_{\aleph}$ are the same constant functions, that is, for all $w \in E$, $f_K(w) = g_{\aleph}(w) = \mathcal{M}$, where $\mathcal{M}$ is a fixed set.

Definition 2.7. (Sezgin et al., 2025b) Let f_K and $g_{\aleph}$ be two $\mathcal{SS}$s. Then, f_K is called a soft A-subset of $g_{\aleph}$, denoted by $f_K \widetilde{\subseteq}_A g_{\aleph}$, if, for each $a, b \in E$, $f_K(a) \subseteq g_{\aleph}(b)$.

Definition 2.8. (Sezgin et al., 2025b) Let f_K and $g_{\aleph}$ be two $\mathcal{SS}$s. Then, f_K is called a soft S-complement of $g_{\aleph}$, denoted by $f_K =_S (g_{\aleph})^c$, if, for all $w \in E, f_K(w) = \mathcal{M}$ and $g_{\aleph}(w) = \mathcal{D}$, where $\mathcal{M}$ and $\mathcal{D}$ are two fixed sets and $\mathcal{M} = \mathcal{D}'$. Here, $\mathcal{D}' = U \backslash \mathcal{D}$.

From now on, let $(G, .)$ be a group, and $S_G(U)$ denotes the collection of all $\mathcal{SS}$s over U, whose parameter sets are G; that is, each element of $S_G(U)$ is an $\mathcal{SS}$ parameterized by G.

Definition 2.9. (Ay and Sezgin, 2025) Let f_G and g_G be two $\mathcal{SS}$s. Then, the soft intersection-gamma product $f_G \otimes_{i/g} g_G$ is defined by

$$\left(f_G \otimes_{i/g} g_G\right)(x) = \bigcap_{x=yz} \left(f_G(y) \gamma g_G(z)\right) = \bigcap_{x=yz} \left(\left(f_G(y)\right)' \cap g_G(z)\right), y, z \in G$$

for all $x \in G$.

For the sake of brevity, from now on, "$y.z$" will be designated by "yz", where $y, z \in G$.

For more on SSs, we refer to Aktas and Çağman (2007), Alcantud et al. (2024), Ali et al. (2015), Ali et al. (2022), Atagün et al. (2019), Atagün and Sezgin (2015), Atagün and Sezer (2015), Atagün and Sezgin (2017), Atagün and Sezgin (2018), Atagün and Sezgin (2022), Feng et al. (2008), Gulistan and Shahzad (2014), Gulistan et al. (2018); Jana et al. (2019), Karaaslan (2019), Khan et al. (2017), Mahmood et al. (2015), Mahmood et al. (2018), Manikantan et al. (2023), Memiş (2022), Özlü and Sezgin (2020), Riaz et al. (2023), Sezer and Atagün (2016), Sezer et al. (2017), Sezer et al. (2013), Sezer et al. (2014), Sezgin et al. (2019), Sezgin and İlgin (2024a, 2024b), Sezgin et al. (2022), Sezgin and Onur (2024), Sezgin et al. (2024a,2024b), Sezgin and Orbay (2022), Sezgin et al., (2025a), Sezgin et al. (2019), Sun et al. (2008), Tunçay and Sezgin (2016), Ullah et al. (2018).

3. SOFT UNION-LAMBDA PRODUCT OF GROUPS

This section presents a rigorous formalization of the soft union–lambda product, a newly proposed binary operation defined over soft sets indexed by group-structured parameter domains. A comprehensive algebraic analysis confirms the operation's fundamental axiomatic properties—namely closure, associativity, commutativity, idempotency, and distributivity over other soft set operations—while demonstrating its compatibility with generalized frameworks of soft equality and soft subsethood. Particular emphasis is placed on elucidating the structural dynamics of the operation within hierarchical lattices of soft inclusion and its seamless integration into the broader algebraic topology underlying soft set theory.

Definition 3.1. Let $\digamma_G$ and $\mathcal{G}_G$ be two $\mathcal{SS}$s. Then, the soft union-lambda product $\digamma_G \otimes_{u/l} \mathcal{G}_G$ is defined by

$$\left(\digamma_G \otimes_{u/l} \mathcal{G}_G\right)(x) = \bigcup_{x=yz} \left(\digamma_G(y) \lambda \mathcal{G}_G(z)\right) = \bigcup_{x=yz} \left(\digamma_G(y) \cup \left(\mathcal{G}_G(z)\right)'\right), y, z \in G$$

for all $x \in G$.

Note here that since G is a group, there always exist $y, z \in G$ such that $= yz$, for all $x \in G$. Let the order of the group G be n, that is, $|G| = n$. Then, it is obvious that there exist n distinct representations for each $x \in G$ such that $x = yz$, where $y, z \in G$.

Note 3.2. The soft union-lambda product is well-defined in $S_G(U)$. In fact, let $\digamma_G, \mathcal{G}_G, \sigma_G, \mathcal{K}_G \in S_G(U)$ such that $(\digamma_G, \mathcal{G}_G) = (\sigma_G, \mathcal{K}_G)$. Then, $\digamma_G = \sigma_G$ and $\mathcal{G}_G = \mathcal{K}_G$, implying that $\digamma_G(x) = \sigma_G(x)$ and $\mathcal{G}_G(x) = \mathcal{K}_G(x)$ for all $x \in G$. Thereby, for all $x \in G$,

$$\begin{aligned}\left(\digamma_G \otimes_{u/l} \mathcal{G}_G\right)(x) &= \bigcup_{x=yz} \left(\digamma_G(y) \cup \mathcal{G}_G{}^c(z)\right) \\ &= \bigcup_{x=yz} \left(\sigma_G(y) \cup \mathcal{K}_G{}^c(z)\right) \\ &= \left(\sigma_G \otimes_{u/l} \mathcal{K}_G\right)(x)\end{aligned}$$

Hence, $\digamma_G \otimes_{u/l} \mathcal{G}_G = \sigma_G \otimes_{u/l} \mathcal{K}_G$.

Example 3.3. Consider the group $\mathfrak{G} = \{\mathfrak{a}, \mathfrak{b}\}$ with the following operation**:**

$\cdot$	$\mathfrak{a}$	$\mathfrak{b}$
$\mathfrak{a}$	$\mathfrak{a}$	$\mathfrak{b}$
$\mathfrak{b}$	$\mathfrak{b}$	$\mathfrak{a}$

Let $\mathcal{f}_G$ and $\mathcal{g}_G$ be two $\mathcal{SS}$s over $U = D_2 = \{< x, y >: x^2 = y^2 = e, xy = yx\} = \{e, x, y, yx\}$ as follows:

$\mathcal{f}_G = \{(\mathfrak{a}, \{e, yx\}), (\mathfrak{b}, \{y\})\}$ and $\mathcal{g}_G = \{(\mathfrak{a}, \{e, x, y\}), (\mathfrak{b}, \{e, x\})\}$

Since $\mathfrak{a} = \mathfrak{a}\mathfrak{a} = \mathfrak{b}\mathfrak{b}$, $\left(\mathcal{f}_G \otimes_{u/l} \mathcal{g}_G\right)(\mathfrak{a}) = \left(\mathcal{f}_G(\mathfrak{a}) \cup {\mathcal{g}_G}^c(\mathfrak{a})\right) \cup \left(\mathcal{f}_G(\mathfrak{b}) \cup {\mathcal{g}_G}^c(\mathfrak{b})\right) = \{e, y, yx\}$ and since $\mathfrak{b} = \mathfrak{a}\mathfrak{b} = \mathfrak{b}\mathfrak{a}$, $\left(\mathcal{f}_G \otimes_{u/l} \mathcal{g}_G\right)(\mathfrak{b}) = \left(\mathcal{f}_G(\mathfrak{a}) \cup {\mathcal{g}_G}^c(\mathfrak{b})\right) \cup \left(\mathcal{f}_G(\mathfrak{b}) \cup {\mathcal{g}_G}^c(\mathfrak{a})\right) = \{e, y, yx\}$ is obtained. Hence,

$\mathcal{f}_G \otimes_{u/l} \mathcal{g}_G = \{(\mathfrak{a}, \{e, y, yx\}), (\mathfrak{b}, \{e, y, yx\})\}$

Proposition 3.4. The set $S_G(U)$ is closed under the soft union-lambda product. That is, if $\mathcal{f}_G$ and $\mathcal{g}_G$ are two $\mathcal{SS}$s, then so is $\mathcal{f}_G \otimes_{u/l} \mathcal{g}_G$.

PROOF. It is obvious that the soft union-lambda product is a binary operation in $S_G(U)$. Thereby, $S_G(U)$ is closed under the soft union-lambda product.

Proposition 3.5. The soft union-lambda product is not associative in $S_G(U)$.

PROOF. Consider the $\mathcal{SS}$s $\mathcal{f}_G$ and $\mathcal{g}_G$ over $U = \{e, x, y, yx\}$ in Example 3.3. Let $\mathcal{h}_G = \{(\mathfrak{a}, \{x\}), (\mathfrak{b}, \{y\})\}$ be a $\mathcal{SS}$. Since $\mathcal{f}_G \otimes_{u/l} \mathcal{g}_G = \{(\mathfrak{a}, \{e, y, yx\}), (\mathfrak{b}, \{e, y, yx\})\}$, then

$$\left(\mathcal{f}_G \otimes_{u/l} \mathcal{g}_G\right) \otimes_{u/l} \mathcal{h}_G = \{(\mathfrak{a}, U), (\mathfrak{b}, U)\}$$

Moreover, since $\mathcal{g}_G \otimes_{u/l} \mathcal{h}_G = \{(\mathfrak{a}, U), (\mathfrak{b}, U)\}$, then

$$\mathcal{f}_G \otimes_{u/l} \left(\mathcal{g}_G \otimes_{u/l} \mathcal{h}_G\right) = \{(\mathfrak{a}, \{e, y, yx\}), (\mathfrak{b}, \{e, y, yx\})\}$$

Thereby, $\left(\mathcal{f}_G \otimes_{u/l} \mathcal{g}_G\right) \otimes_{u/l} \mathcal{h}_G \neq \mathcal{f}_G \otimes_{u/l} \left(\mathcal{g}_G \otimes_{u/l} \mathcal{h}_G\right)$. □

Proposition 3.6. The soft union-lambda product is not commutative in $S_G(U)$.

PROOF. Consider the $\mathcal{SS}$s $\mathcal{f}_G$ and $\mathcal{g}_G$ over $U = \{e, x, y, yx\}$ in Example 3.3. Then,

$\mathcal{f}_G \otimes_{u/l} \mathcal{g}_G = \{(\mathfrak{a}, \{e, y, yx\}), (\mathfrak{b}, \{e, y, yx\})\}$ and $\mathcal{g}_G \otimes_{u/l} \mathcal{f}_G = \{(\mathfrak{a}, U), (\mathfrak{b}, U)\}$

implying that $\mathcal{f}_G \otimes_{u/l} \mathcal{g}_G \neq \mathcal{g}_G \otimes_{u/l} \mathcal{f}_G$. □

Proposition 3.7. The soft union-lambda product is not idempotent in $S_G(U)$.

PROOF. Consider the $\mathcal{SS}$ in Example 3.3. Then,

$\mathcal{f}_G \otimes_{u/l} \mathcal{f}_G = \{(\mathfrak{Q}, U), (\mathfrak{b}, U)\}$

implying that $\mathcal{f}_G \otimes_{u/l} \mathcal{f}_G \neq \mathcal{f}_G$. □

Proposition 3.8. Let $\mathcal{f}_G$ be a constant $\mathcal{SS}$. Then, $\mathcal{f}_G \otimes_{u/l} \mathcal{f}_G = U_G$.

PROOF. Let $\mathcal{f}_G$ be a constant $\mathcal{SS}$ such that, for all $x \in G$, $\mathcal{f}_G(x) = A$, where A is a fixed set. Hence, for all $x \in G$,

$$\left(\mathcal{f}_G \otimes_{u/l} \mathcal{f}_G\right)(x) = \bigcup_{x=yz} \left(\mathcal{f}_G(y) \cup \mathcal{f}_G{}^c(z)\right) = U_G(x)$$

Thereby, $\mathcal{f}_G \otimes_{u/l} \mathcal{f}_G = U_G$. □

Note that since G is a group, there always exist $y, z \in G$ such that $= yz$, for all $x \in G$, and there exist n distinct representations for each $x \in G$ such that $x = yz$, where $y, z \in G$ and $|G| = n$. Hence, $\mathcal{f}_G \otimes_{u/l} \mathcal{f}_G = U_G$ whether $\mathcal{f}_G$ is a constant $\mathcal{SS}$ or not.

Remark 3.9. Let $S_G{}^*(U)$ be the collection of all constant $\mathcal{SS}$s. Then, the soft intersection-star product is not idempotent in $S_G{}^*(U)$ either.

Proposition 3.10. U_G is the left absorbing element of the soft union-lambda product in $S_G(U)$.

PROOF. Let $x \in G$. Then, for all $x \in G$,

$$\left(U_G \otimes_{u/l} \mathcal{f}_G\right)(x) = \bigcup_{x=yz} \left(U_G(y) \cup \mathcal{f}_G{}^c(z)\right) = \bigcup_{x=yz} \left(U \cup \mathcal{f}_G{}^c(z)\right) = U_G(x)$$

Thus, $U_G \otimes_{u/l} \mathcal{f}_G = U_G$. □

Proposition 3.11. U_G is not the right absorbing element of the soft union-lambda product in $S_G(U)$.

PROOF. Consider the $\mathcal{SS}$ $\mathcal{f}_G$ in Example 3.3. Then,

$$\mathcal{f}_G \otimes_{u/l} U_G = \{(\mathfrak{Q}, \{e, y, yx\}), (\mathfrak{b}, \{e, y, yx\})\}$$

implying that, $\mathcal{f}_G \otimes_{u/l} U_G \neq U_G$. □

Remark 3.12. U_G is not the absorbing element of the soft union-lambda product in $S_G(U)$.

Proposition 3.13. Let $\mathcal{f}_G$ be a constant $\mathcal{SS}$. Then, $\mathcal{f}_G \otimes_{u/l} U_G = \mathcal{f}_G$.

PROOF**.** Let $\digamma_G$ be a constant $\mathcal{SS}$ such that, for all $x \in G$, $\digamma_G(x) = A$, where A is a fixed set. Hence, for all $x \in G$,

$$\left(\digamma_G \otimes_{u/l} U_G\right)(x) = \bigcup_{x=yz} \left(\digamma_G(y) \cup {U_G}^c(z)\right) = \bigcup_{x=yz} \left(\digamma_G(y) \cup \emptyset\right) = \digamma_G(x)$$

Thereby, $\digamma_G \otimes_{u/l} U_G = \digamma_G$. □

Remark 3.14. U_G is the right identity element of the soft union-lambda product in ${S_G}^*(U)$ by Proposition 3.10 and Proposition 3.13.

Proposition 3.15. Let $\digamma_G$ be a constant $\mathcal{SS}$. Then, $\emptyset_G \otimes_{u/l} \digamma_G = {\digamma_G}^c$.

PROOF**.** Let $\digamma_G$ be a constant $\mathcal{SS}$ such that, for all $x \in G$, $\digamma_G(x) = A$, where A is a fixed set. Hence, for all $x \in G$,

$$\left(\emptyset_G \otimes_{u/l} \digamma_G\right)(x) = \bigcup_{x=yz} \left(\emptyset_G(y) \cup {\digamma_G}^c(z)\right) = \bigcup_{x=yz} \left(\emptyset \cup {\digamma_G}^c(z)\right) = {\digamma_G}^c(x)$$

Thereby, $\emptyset_G \otimes_{u/l} \digamma_G = {\digamma_G}^c$. □

Proposition 3.16. Let $\digamma_G$ and $\mathcal{G}_G$ be two $\mathcal{SS}$s. Then, $\digamma_G \otimes_{u/l} \emptyset_G = U_G$.

PROOF. Let $\digamma_G$ be a $\mathcal{SS}$s. Then, for all $x \in G$,

$$\left(\digamma_G \otimes_{u/l} \emptyset_G\right)(x) = \bigcup_{x=yz} \left(\digamma_G(y) \cup {\emptyset_G}^c(z)\right) = \bigcup_{x=yz} \left(\digamma_G(y) \cup U\right) = U_G(x)$$

Thereby, $\digamma_G \otimes_{u/l} \mathcal{G}_G = U_G$. □

Proposition 3.17. Let $\digamma_G$ be a constant $\mathcal{SS}$. Then, $\digamma_G \otimes_{u/l} {\digamma_G}^c = \digamma_G$.

PROOF**.** Let $\digamma_G$ be a constant $\mathcal{SS}$ such that, for all $x \in G$, $\digamma_G(x) = A$, where A is a fixed set. Hence, for all $x \in G$,

$$\left(\digamma_G \otimes_{u/l} {\digamma_G}^c\right)(x) = \bigcup_{x=yz} \left(\digamma_G(y) \cup ({\digamma_G}^c)^c(z)\right) = \digamma_G(x)$$

Thereby, $\digamma_G \otimes_{u/l} {\digamma_G}^c = \digamma_G$. □

Proposition 3.18. Let $\digamma_G$ be a constant $\mathcal{SS}$. Then, ${\digamma_G}^c \otimes_{u/l} \digamma_G = {\digamma_G}^c$.

PROOF**.** Let $\digamma_G$ be a constant $\mathcal{SS}$ such that, for all $x \in G$, $\digamma_G(x) = A$, where A is a fixed set. Hence, for all $x \in G$,

$$\left({\digamma_G}^c \otimes_{u/l} \digamma_G\right)(x) = \bigcup_{x=yz} \left({\digamma_G}^c(y) \cup {\digamma_G}^c(z)\right) = {\digamma_G}^c(x)$$

Thereby, ${\digamma_G}^c \otimes_{u/l} \digamma_G = {\digamma_G}^c$. □

Proposition 3.19. Let $\digamma_G$ and $\mathcal{G}_G$ be two $\mathcal{SS}$s. If $\mathcal{G}_G \,\tilde{\subseteq}_A\, \digamma_G$, then $\digamma_G \otimes_{u/l} \mathcal{G}_G = U_G$.

PROOF. Let $\digamma_G$ and $\mathcal{G}_G$ be two $\mathcal{SS}$s. Suppose that $\mathcal{G}_G \widetilde{\subseteq}_A \digamma_G$. Then, $\mathcal{G}_G(y) \subseteq \digamma_G(z)$, for each $y, z \in G$. Since $\digamma_G(y) \cup \mathcal{G}_G{}^c(z) = (\mathcal{G}_G(z) \backslash (\digamma_G(y))'$, for all $y, z \in G$,

$$\left(\digamma_G \otimes_{u/l} \mathcal{G}_G\right)(x) = \bigcup_{x=yz} \left(\digamma_G(y) \cup \mathcal{G}_G{}^c(z)\right) = U = U_G(x)$$

for all $x \in G$, Thereby, $\digamma_G \otimes_{u/l} \mathcal{G}_G = U_G$.

Proposition 3.20. Let $\digamma_G$ and $\mathcal{G}_G$ be two $\mathcal{SS}$s. If $\mathcal{G}_G \subseteq_S \digamma_G$, then, $\digamma_G \otimes_{u/l} \mathcal{G}_G = U_G$.

PROOF**.** The proof is similar to the proof of Proposition 3.19.

Proposition 3.21. Let $\digamma_G$ and $\mathcal{G}_G$ be two $\mathcal{SS}$s. If $\digamma_G \widetilde{\subseteq}_S (\mathcal{G}_G{}^c)$, then $\digamma_G \otimes_{u/l} \mathcal{G}_G = \mathcal{G}_G{}^c$.

PROOF. Let $\digamma_G$ and $\mathcal{G}_G$ be two $\mathcal{SS}$s and $\digamma_G \widetilde{\subseteq}_S (\mathcal{G}_G{}^c)$. Hence, for all $x \in G, \digamma_G(x) = A$ and $\mathcal{G}_G(x) = B$, where A and B are two fixed sets and $A \subseteq B'$. Thus, for all $x \in G$,

$$\left(\digamma_G \otimes_{u/l} \mathcal{G}_G\right)(x) = \bigcup_{x=yz} \left(\digamma_G(y) \cup \mathcal{G}_G{}^c(z)\right) = \mathcal{G}_G{}^c(x)$$

Thereby, $\digamma_G \otimes_{u/l} \mathcal{G}_G = \mathcal{G}_G{}^c$. □

Proposition 3.22. Let $\digamma_G$ and $\mathcal{G}_G$ be two $\mathcal{SS}$s. If $(\mathcal{G}_G{}^c) \widetilde{\subseteq}_S \digamma_G$, then $\digamma_G \otimes_{u/l} \mathcal{G}_G = \digamma_G$.

PROOF. Let $\digamma_G$ and $\mathcal{G}_G$ be two $\mathcal{SS}$s and $(\mathcal{G}_G{}^c) \widetilde{\subseteq}_S \digamma_G$. Hence, for all $x \in G, \digamma_G(x) = A$ and $\mathcal{G}_G(x) = B$, where A and B are two fixed sets and $B' \subseteq A$. Thus, for all $x \in G$,

$$\left(\digamma_G \otimes_{u/l} \mathcal{G}_G\right)(x) = \bigcup_{x=yz} \left(\digamma_G(y) \cup \mathcal{G}_G{}^c(z)\right) = \digamma_G(x)$$

Thereby, $\digamma_G \otimes_{u/l} \mathcal{G}_G = \digamma_G$. □

Proposition 3.23. Let $\digamma_G$ and $\mathcal{G}_G$ be two $\mathcal{SS}$s. If $\digamma_G =_S (\mathcal{G}_G)^c$, then, $\digamma_G \otimes_{u/l} \mathcal{G}_G = \digamma_G$.

PROOF**.** Let $\digamma_G$ and $\mathcal{G}_G$ be two $\mathcal{SS}$s and $\digamma_G =_S (\mathcal{G}_G)^c$. Hence, for all $x \in G, \digamma_G(x) = A$ and $\mathcal{G}_G(x) = B$, where A and B are two fixed sets and $A = B'$. Thus, for all $x \in G$,

$$\left(\digamma_G \otimes_{u/l} \mathcal{G}_G\right)(x) = \bigcup_{x=yz} \left(\digamma_G(y) \cup \mathcal{G}_G{}^c(z)\right) = \digamma_G(y)$$

Thereby, $\digamma_G \otimes_{u/l} \mathcal{G}_G = \digamma_G$. □

Proposition 3.24. Let $\digamma_G$ and $\mathcal{G}_G$ be two $\mathcal{SS}$s. Then, $\left(\digamma_G \otimes_{u/l} \mathcal{G}_G\right)^c = \digamma_G \otimes_{i/g} \mathcal{G}_G$.

PROOF. Let $\digamma_G$ and $\mathcal{G}_G$ be two $\mathcal{SS}$s. Then, for all $x \in G$,

$$\left(\digamma_G \otimes_{u/l} \mathcal{G}_G\right)^c(x) = \left(\bigcup_{x=yz} \digamma_G(y) \cup \mathcal{G}_G{}^c(z)\right)'$$

$$= \bigcap_{x=yz} \left(\digamma_G(y) \cup \mathcal{G}_G{}^c(z)\right)'$$
$$= \bigcap_{x=yz} \left(\digamma_G{}^c(y) \cap \mathcal{G}_G(z)\right)$$
$$= \left(\digamma_G \otimes_{i/g} \mathcal{G}_G\right)(x)$$

Thereby. $\left(\digamma_G \otimes_{u/l} \mathcal{G}_G\right)^c = \digamma_G \otimes_{i/g} \mathcal{G}_G$. □

Proposition 3.25. Let $\digamma_G$, $\mathcal{G}_G$, and $\hbar_G$ be three $\mathcal{SS}$s. If $\digamma_G \tilde{\subseteq} \mathcal{G}_G$, then $\digamma_G \otimes_{u/l} \hbar_G \tilde{\subseteq} \mathcal{G}_G \otimes_{u/l} \hbar_G$ and $\hbar_G \otimes_{u/l} \mathcal{G}_G \tilde{\subseteq} \hbar_G \otimes_{u/l} \digamma_G$.

PROOF. Let $\digamma_G$, $\mathcal{G}_G$, and $\hbar_G$ be three $\mathcal{SS}$s such that $\digamma_G \tilde{\subseteq} \mathcal{G}_G$. Then, for all $x \in G$, $\digamma_G(x) \subseteq \mathcal{G}_G(x)$ and $\mathcal{G}_G{}^c(x) \subseteq \digamma_G{}^c(x)$. Thus, for all $x \in G$,

$$\left(\digamma_G \otimes_{u/l} \hbar_G\right)(x) = \bigcup_{x=yz} \left(\digamma_G(y) \cup \hbar_G{}^c(z)\right)$$
$$\subseteq \bigcup_{x=yz} \left(\mathcal{G}_G(y) \cup \hbar_G{}^c(z)\right)$$
$$= \left(\mathcal{G}_G \otimes_{u/l} \hbar_G\right)(x)$$

for all $x \in G$, implying that $\digamma_G \otimes_{u/l} \hbar_G \tilde{\subseteq} \mathcal{G}_G \otimes_{u/l} \hbar_G$. Similarly, for all $x \in G$,

$$\left(\hbar_G \otimes_{u/l} \mathcal{G}_G\right)(x) = \bigcup_{x=yz} \left(\hbar_G(y) \cup \mathcal{G}_G{}^c(z)\right)$$
$$\subseteq \bigcup_{x=yz} \left(\hbar_G(y) \cup \digamma_G{}^c(z)\right)$$
$$= \left(\hbar_G \otimes_{u/l} \digamma_G\right)(x)$$

implying that $\hbar_G \otimes_{u/l} \mathcal{G}_G \tilde{\subseteq} \hbar_G \otimes_{u/l} \digamma_G$. □

Proposition 3.26. Let $\digamma_G$, $\mathcal{G}_G$, $\mathcal{O}_G$, and $\mathcal{K}_G$ be four $\mathcal{SS}$s. If $\mathcal{O}_G \tilde{\subseteq} \digamma_G$ and $\mathcal{K}_G \tilde{\subseteq} \mathcal{G}_G$, then $\mathcal{O}_G \otimes_{u/l} \mathcal{G}_G \tilde{\subseteq} \digamma_G \otimes_{u/l} \mathcal{K}_G$ and $\mathcal{K}_G \otimes_{u/l} \digamma_G \tilde{\subseteq} \mathcal{G}_G \otimes_{u/l} \mathcal{O}_G$.

PROOF. Let $\digamma_G$, $\mathcal{G}_G$, $\mathcal{O}_G$, and $\mathcal{K}_G$ be four $\mathcal{SS}$s such that $\mathcal{O}_G \tilde{\subseteq} \digamma_G$ and $\mathcal{K}_G \tilde{\subseteq} \mathcal{G}_G$. Then, for all $x \in G$, $\mathcal{O}_G(x) \subseteq \digamma_G(x)$ and $\mathcal{K}_G(x) \subseteq \mathcal{G}_G(x)$. Thus, $\digamma_G{}^c(x) \subseteq \mathcal{O}_G{}^c(x)$ and $\mathcal{G}_G{}^c(x) \subseteq \mathcal{K}_G{}^c(x)$ for all $x \in G$. Thus,

$$\left(\mathcal{O}_G \otimes_{u/l} \mathcal{G}_G\right)(x) = \bigcup_{x=yz} \left(\mathcal{O}_G(y) \cup \mathcal{G}_G{}^c(z)\right)$$
$$\subseteq \bigcup_{x=yz} \left(\digamma_G(y) \cup \mathcal{K}_G{}^c(z)\right)$$
$$= \left(\digamma_G \otimes_{u/l} \mathcal{K}_G\right)(x)$$

implying that $\mathcal{O}_G \otimes_{u/l} \mathcal{G}_G \tilde{\subseteq} \digamma_G \otimes_{u/l} \mathcal{K}_G$. Similarly, for all $x \in G$,

$$\left(\mathcal{K}_G \otimes_{u/l} \digamma_G\right)(x) = \bigcup_{x=yz} \left(\mathcal{K}_G(y) \cup \digamma_G{}^c(z)\right)$$

$$\subseteq \bigcup_{x=yz} \left(\mathcal{g}_G(y) \cup \sigma_G{}^c(z)\right)$$
$$= \left(\mathcal{g}_G \otimes_{u/l} \sigma_G\right)(x)$$

is obtained, implying that $\mathcal{h}_G \otimes_{u/l} \mathcal{f}_G \cong \mathcal{g}_G \otimes_{u/l} \sigma_G$. □

Proposition 3.27. The soft union-lambda product distributes over the union operation of $\mathcal{SS}$s from the right side.

PROOF. Let $\mathcal{f}_G$, $\mathcal{g}_G$, and $\hbar_G$ be three $\mathcal{SS}$s. Then, for all $x \in G$,

$$\left((\mathcal{f}_G \,\tilde{\cup}\, \mathcal{g}_G) \otimes_{u/l} \hbar_G\right)(x) = \bigcup_{x=yz} \left((\mathcal{f}_G \,\tilde{\cup}\, \mathcal{g}_G)(y) \cup \hbar_G{}^c(z)\right)$$
$$= \bigcup_{x=yz} \left(\left(\mathcal{f}_G(y) \cup \mathcal{g}_G(y)\right) \cup \hbar_G{}^c(z)\right)$$
$$= \bigcup_{x=yz} \left(\left(\mathcal{f}_G(y) \cup \hbar_G{}^c(z)\right) \cup \left(\mathcal{g}_G(y) \cup \hbar_G{}^c(z)\right)\right)$$

$$= \left[\bigcup_{x=yz} \left(\mathcal{f}_G(y) \cup \hbar_G{}^c(z)\right)\right] \cup \left[\bigcup_{x=yz} \left(\mathcal{g}_G(y) \cup \hbar_G{}^c(z)\right)\right]$$
$$= \left(\mathcal{f}_G \otimes_{u/l} \hbar_G\right)(x) \cup \left(\mathcal{g}_G \otimes_{u/l} \hbar_G\right)(x)$$
$$= \left(\left(\mathcal{f}_G \otimes_{u/l} \hbar_G\right) \,\tilde{\cup}\, \left(\mathcal{g}_G \otimes_{u/l} \hbar_G\right)\right)(x)$$

Thus, $(\mathcal{f}_G \,\tilde{\cup}\, \mathcal{g}_G) \otimes_{u/l} \hbar_G = \left(\mathcal{f}_G \otimes_{u/l} \hbar_G\right) \,\tilde{\cup}\, \left(\mathcal{g}_G \otimes_{u/l} \hbar_G\right)$. □

Example 3.28. Consider the group G in Example 3.3. Let $\mathcal{f}_G$, $\mathcal{g}_G$, and $\hbar_G$ be three $\mathcal{SS}$s over $U = \{e, x, y, yx\}$ as follows:

$$\mathcal{f}_G = \{(\mathfrak{A}, \{e, yx\}), (\mathfrak{b}, \{y\})\},\ \mathcal{g}_G = \{(\mathfrak{A}, \{e, x, y\}), (\mathfrak{b}, \{e, x\})\},\ \hbar_G = \{(\mathfrak{A}, \{x\}), (\mathfrak{b}, \{y\})\}$$

Since $\mathcal{f}_G \otimes_{u/l} \hbar_G = \{(\mathfrak{A}, U), (\mathfrak{b}, U)\}$ and $\mathcal{g}_G \otimes_{u/l} \hbar_G = \{(\mathfrak{A}, U), (\mathfrak{b}, U)\}$, then

$$\left(\mathcal{f}_G \otimes_{u/l} \hbar_G\right) \,\tilde{\cup}\, \left(\mathcal{g}_G \otimes_{u/l} \hbar_G\right) = \{(\mathfrak{A}, U), (\mathfrak{b}, U)\}$$

Moreover, since $\mathcal{f}_G \,\tilde{\cup}\, \mathcal{g}_G = \{(\mathfrak{A}, U), (\mathfrak{b}, \{e, x, y\})\}$

$$(\mathcal{f}_G \,\tilde{\cup}\, \mathcal{g}_G) \otimes_{u/l} \hbar_G = \{(\mathfrak{A}, U), (\mathfrak{b}, U)\}$$

Thus, $(\mathcal{f}_G \,\tilde{\cup}\, \mathcal{g}_G) \otimes_{u/l} \hbar_G = \left(\mathcal{f}_G \otimes_{u/l} \hbar_G\right) \,\tilde{\cup}\, \left(\mathcal{g}_G \otimes_{u/l} \hbar_G\right)$. □

Proposition 3.29. The soft union-lambda product does not distribute over the union operation of $\mathcal{SS}$s from the left side.

PROOF. Consider the group G in Example 3.3. Let $\mathcal{f}_G$, $\mathcal{g}_G$, and $\hbar_G$ be three $\mathcal{SS}$s over $U = \{e, x, y, yx\}$ as follows:

$$\mathcal{f}_G = \{(\mathfrak{A}, \{e, yx\}), (\mathfrak{b}, \{y\})\},\ \mathcal{g}_G = \{(\mathfrak{A}, \{e, x, y\}), (\mathfrak{b}, \{e, x\})\},\ \hbar_G = \{(\mathfrak{A}, \{x\}), (\mathfrak{b}, \{y\})\}$$

Since $\mathcal{f}_G \otimes_{u/l} \hbar_G = \{(\mathfrak{A}, U), (\mathfrak{b}, U)\}$ and $\mathcal{f}_G \otimes_{u/l} \mathcal{g}_G = \{(\mathfrak{A}, \{e, y, yx\}), (\mathfrak{b}, \{e, y, yx\})\}$, then

$$\left(\mathcal{f}_G \otimes_{u/l} \hbar_G\right) \tilde{\cup} \left(\mathcal{f}_G \otimes_{u/l} \mathcal{g}_G\right) = \{(\mathfrak{A}, U), (\mathfrak{b}, U)\}$$

Moreover, since $\mathcal{g}_G \tilde{\cup} \hbar_G = \{(\mathfrak{A}, \{e, x, y\}), (\mathfrak{b}, \{e, x, y\})\}$

$$\mathcal{f}_G \otimes_{u/l} (\mathcal{g}_G \tilde{\cup} \hbar_G) = \{(\mathfrak{A}, \{e, y, yx\}), (\mathfrak{b}, \{e, y, yx\})\}$$

Thus, $\mathcal{f}_G \otimes_{u/l} (\mathcal{g}_G \tilde{\cup} \hbar_G) \neq \left(\mathcal{f}_G \otimes_{u/l} \mathcal{g}_G\right) \tilde{\cup} \left(\mathcal{f}_G \otimes_{u/l} \hbar_G\right)$. □

Remark 3.30. The soft union-lambda product does not distribute over the union operation of $\mathcal{SS}$s from both sides.

4. CONCLUSION

This paper introduces the soft union–lambda product, a novel binary operation defined on soft sets over parameter domains endowed with a group-theoretic structure. Through an exhaustive algebraic investigation, the operation is analyzed in terms of its behavior across stratified hierarchies of soft subsethood and its adherence to generalized formulations of soft equality. Positioned within a comparative framework vis-à-vis established binary soft operations, the expressive capacity and structural integrity of the proposed product are critically assessed. The operation's interaction with null and absolute soft sets, as well as its algebraic relationships with other group-based soft constructions, is meticulously examined, highlighting its integrative role within the overarching algebraic topology of soft set theory. Formulated within a rigorous axiomatic schema, the study verifies a suite of essential algebraic invariants—including closure, associativity, commutativity, idempotency, and distributivity—while also addressing the existence or absence of identity, inverse, and absorbing elements. The resulting structure demonstrates formal consistency and internal coherence, establishing the operation as a natural and principled extension of classical algebraic systems into the soft set domain. At a deeper level, this product furnishes the conceptual and algebraic scaffolding for a generalized theory of soft groups, wherein soft sets indexed by group-structured parameters simulate classical group axioms through precisely defined soft operations. Beyond its foundational significance, the framework developed herein advances the algebraic machinery of soft set theory. It paves the way for novel applications in abstract algebraic modeling, generalized soft equalities, and uncertainty-aware decision analysis.

Author Contributions
Xxx

Conflicts of Interest
The authors declare that they have no conflicts of interest regarding the publication of this paper.

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SILENT DETAILS OF URBAN IDENTITY: FUNCTIONAL AND AESTHETIC ASPECTS OF URBAN FURNITURE ON GURES STREET, SIIRT

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Abstract: The development of technology, changes in living habits, and the rapid urbanization process have increased interaction between cities, leading to the formation of cities that are increasingly similar, lacking distinct identities and aesthetic appeal. In this process, urban furniture that shapes the urban space plays a crucial role in constructing both visual aesthetics and urban identity. Urban furniture not only enhances user comfort but also embodies components of identity that reflect the city's historical, cultural, and physical characteristics. This study aims to evaluate the aesthetic qualities of urban furniture on Gures Street in Siirt city centre and its relationship with urban identity. In the research, which was carried out by on-site observation, photo documentation and qualitative analysis methods; seating units, garbage bins, delimitation elements, artistic objects, tree grates, parking spaces, lighting components and water elements were examined in terms of functionality, visual harmony, maintenance status and connection with local identity. The findings show that although the furniture elements meet the needs at the functional level, they contain designs that fall short of aesthetic integrity and fail to align with the regional cultural context. This situation weakens the original identity of the street and creates discontinuity in urban perception. The study reveals that urban furniture should be reconsidered not only as physical objects but also as aesthetic elements with cultural meaning.

Keywords: Public space, Urban aesthetics, Urban identity, Urban furniture, Spatial integrity.

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1. INTRODUCTION

Throughout history, cities have functioned not only as living spaces but also as aesthetic structures that carry social memory (Lynch, 1960). In this context, urban furniture has evolved from being merely physical structures that meet basic needs to becoming important elements that shape urban identity and influence aesthetic perception (Morgan et al., 2000; Grabiec et al., 2022). Urban furniture refers to a set of physical elements designed to facilitate and direct

the daily lives of individuals in public open spaces of cities, while also providing spatial comfort (Akyol, 2006; Arruda et al., 2017). Consisting of components such as seating units, lighting elements, litter bins, flower boxes, directional boards and boundary elements, these structures are not only functional but also have aesthetic, cultural and symbolic meanings (Aksu, 2012; Arruda et al., 2017; Uslu and Bolukbasi, 2019; Grabiec et al., 2022). For this reason, urban furniture plays a crucial role not only in the interaction between individuals and their surroundings but also in shaping the formation of urban identity and the perceptual integrity of space (Lynch, 1960; Carmona, 2021).

When urban furniture is designed in consideration of the historical, cultural, and natural context of the environment, it also contributes to the establishment of an emotional bond between the user and the city (Bayramoglu and Ozdemir, 2012). Original urban furniture, with high aesthetic value and reflecting the local identity, strengthens the sense of place by enhancing the authenticity of the space. On the other hand, standard and unidentified furniture creates uniformity in the urban environment and weakens the sense of belonging (Relph, 1976; Mieczkowski, 1985; Rossi, 2006; Ziyaee, 2018) In this context, supporting the principal pedestrian axes, especially in city centres, with identity and meaningful furnishings serves to protect social memory and enhance urban aesthetics (Bayramoglu and Ozdemir, 2012; Yücel, 2013).

Urban identity encompasses the totality of spatial and symbolic qualities that are specific to a city, shaped by its historical accumulation, geographical structure, architectural character, cultural codes, and social memory (Lynch, 1960; Matzarakis and Mayer, 1996; Ziyaee, 2018). The original building elements, street textures, squares, and open spaces in different layers of the city serve as visual and perceptual carriers of this identity (Stathopoulos et al., 2004; Birol, 2007; Gul, 2013; Guler et al., 2016). In this context, urban furniture in public spaces should be considered not only as technical elements, but also as cultural indicators that reflect urban memory. In cities with a unique urban identity, furniture incorporates cultural references such as local materials, colors, patterns, and forms, thereby reinforcing the individual's sense of belonging and meaning (Relph, 1976; Matzarakis et al., 2007; Arruda et al., 2017).

Urban aesthetics, on the other hand, is concerned with the visual harmony, formal coherence and artistic value of a city's spatial arrangements (Wang, 2018). Aesthetic integrity is ensured not only by architectural composition but also by micro-scale design decisions such as the correct placement of urban furniture, proportionality, and harmony with the surroundings (Nikolopoulou and Steemers, 2003; Nia and Olugbenga, 2020). A lack of aesthetics, haphazardly placed or visually complex furnishings reduce the spatial quality of the city; on the other hand, original and remarkable designs that contain linguistic unity, are related to the city, increase aesthetic perception and encourage the use of public spaces (Carmona, 2021; Grabiec et al., 2022).

In the literature, it has been noted that well-designed urban furniture fosters a sense of belonging and a 'sense of place' among city dwellers (Toy et al., 2007; Yilmaz et al., 2013; Yücel, 2006; Arruda et al., 2017; Grabiec et al., 2022). Furthermore, similar and anonymous designs can lead to a weakening of urban identity by increasing perceptions of 'loss of place' (Relph, 1976; Schulz, 1980; Nia and Olugbenga, 2020). Urban furniture in public spaces can be designed elements that reveal the character and identity of the city (Arruda et al., 2017). Especially the streets in the city centres are the places where these furnishings have the most intense contact with the city dwellers (Yucel, 2006; Bayazit and Kisakurek, 2020). Furniture that embodies an urban identity is characterized by a unique combination of city-specific elements, including

materials, forms, and historical textures (Lynch, 1960). Aesthetics is the external reflection of this character. Facilities without identity reduce the perceptual value of the space (Kır, 2009; Bayazit and Kisakurek, 2020).

The focus of this study is to evaluate the existing urban furniture in Siirt's Gures Street in terms of identity and aesthetics. Gures Street, one of the most prominent and symbolic urban axes in Siirt, is a central space for Siirt, encompassing areas of economic, social, cultural, and political activity. In this context, the aim is to evaluate the urban furniture on Gures Street in terms of both its urban aesthetic appeal and its capacity to represent the area's identity. The study is based on the idea that this pedestrian axis is not only a transportation line, but also a representational medium where urban memory is visually encoded. In this context, the study aims to evaluate the urban furniture in the study area in terms of its aesthetic appeal and suitability for enhancing Siirt's urban identity.

2. MATERIAL AND METHOD

This study employs a qualitative research method and aims to analyze urban furniture in the context of aesthetic and identity values. The research process is based on observation, visual document analysis, literature review, and photo-based descriptive analysis techniques. The primary material of the study consists of original ground photographs taken on Gures Street and Siirt Gures Street in March and April 2025, as well as qualitative data obtained from field observations.

Gures Street is one of the most prominent and symbolic urban axes of Siirt. The street, which is approximately 2.236 meters long, extends from northwest to southeast, from Seyh Aziz Street to Ibrahim Hakki Street. The pedestrian section is pedestrianized and then opened to vehicular traffic, connecting to the ring road (Gunduz Gezer, 2022). The street, which was included in the zoning plan in the late 1970s, has become the focal point of Siirt's social, economic, and cultural life over time (Ozgen and Karadogan, 2009). In 2006, pedestrianization was implemented based on a project prepared by the Ankara Metropolitan Municipality, and the street gained the identity of an important public space where urban interaction intensified (Gunduz Gezer, 2022). Today, Gures Street is not only the city's main pedestrian thoroughfare but also a multifaceted public space that combines various functions, including shopping, recreation, socializing, and meeting. The street not only shapes the city centre but also serves as a spatial reference that determines the direction of urban development (Derin, 2021; Demir, 2023).

The various cafes, restaurants, health and education institutions, and commercial centers located on the route bring together different socio-economic groups, thus exhibiting a multicultural urban structure (Gunduz Gezer, 2022; Tan and Bayezit, 2023). Although located in the historical core area, it has also contributed to the spatial development of the new Siirt through the modernization process. The location of Siirt University, situated near the city centre, has directly influenced the transformation of the street, resulting in the emergence of a lively and dynamic social environment where the young population is primarily concentrated. In this context, Gures Street is regarded as a strong urban image that symbolizes the transition to contemporary urban life while preserving traditional values (Figure 1).

The research design is based on a case study, with Siirt Gures Street serving as the single sample. During the field study, the urban furniture (benches, litter bins, lamp posts, boundary elements, flower boxes, and floor coverings) in the street was observed on-site, and each item

was evaluated in terms of aesthetic integrity, functionality, spatial harmony, identity reflection, and user-friendliness.

All observations were made using a semi-structured field survey form, and the visual analysis was supported by photographic documentation. The evaluation criteria were structured around the central themes defined in the national and international literature on urban furniture, including aesthetic value, representation of local identity, ergonomic functionality, ease of maintenance, and durability.

Figure 1. Location of the study area (Google Earth, 2025) and images of Gures Street (Siirt Directorate of Culture and Tourism, 2025)

3. RESULTS

In this section, urban furniture in Gures Street, Siirt, has been evaluated in terms of aesthetic value, functionality, and contribution to urban identity. Based on on-site observations and photographic documentation, the following elements were analyzed under separate headings: seating units, waste bins, lighting elements, flower boxes, border elements, and floor coverings.

3.1. Seating elements

Three types of seating elements were identified in the study area: under-tree seating, with and without backs, and all models are without armrests (Akyol, 2006).

In general, the seating units are simple in design. Seating units in the street are generally classic bench models with metal frames and wooden seats. In general, the materials of the seats are worn, and in some places, the backrest is broken or missing. The seating units are in completely open areas, with no shelter. Their open position in the sun and lack of shade reduce the comfort of use. The wooden parts are dilapidated and irregular in appearance. During the field study

observations, it was noted that these benches have a general shape that can be found in any city. The designs do not contain any aesthetic elements relating to urban identity, motifs, or symbols specific to Siirt. Therefore, they are weak in terms of urban identity. Aesthetically, they are compatible with the street structure and have a functional appearance (Figure 2).

In some areas, circular bench systems have been used around the tree. These models are out of scale with the tree, narrow,

and unevenly mounted. The wooden parts are of different colors, and some are missing, disrupting the visual integrity. They are of low aesthetic quality and do not contribute to the urban identity. Figure 3 illustrates various types of bolted boards, some of which are missing or damaged. This poses a risk in terms of both aesthetics and safety.

3.2. Lighting elements

The modern, slim-line lighting poles used along the street feature a minimalist design and contemporary lines. The design of the poles used on Gures Street consists of a tubular body that narrows towards one end and features visual objects on top. Although aesthetically unified, these elements are not related to traditional local architectural elements. The lighting elements in the study area do not carry symbols specific to Siirt and exhibit a thoroughly contemporary style. Although they fulfil functionality by providing appropriate light intensity, their aesthetic identity value is limited. All poles are similar in tone and are not visually incompatible with the street texture; however, they are not unique. During the field inspections, it was observed that the poles were positioned at the border of the vegetative landscape in the areas where they were located, or in some cases, they were planted solely for aesthetic purposes (Figure 4).

Figure 2**.** Seating elements located in the study area on Gures Street

Figure 3. Tree-surround seating elements located in the study area on Gures Street

Figure 4. Lighting elements located in the study area on Gures Street

3.3. Rubbish bins

The bins used along Gures Street are rectangular with metal frames and horizontal wooden slats. The bins placed on the street have been partially enriched visually by using wood veneer on metal. Although this design is positive in terms of providing aesthetic integrity, the selected wood patterns or colors do not contain any cultural reference specific to Siirt. Although the combination of artificial and natural materials harmonizes with the area, it does not establish a direct connection with the city's symbolic identity. These bins are suitable for the area in terms of functionality and general aesthetics, but they fall short of creating a unique urban identity (Figure 5). Additionally, it was determined that their number was insufficient, and their placement was incompatible.

3.4. Delimitation elements

There are different types and materials of delimitation elements (metal fences, parking stones, short, fixed barriers, and illuminated lights) on Gures Street. However, field observations revealed that these elements are not adequate in terms of design, placement, and maintenance. Metal fences between the planted areas and the pedestrian path serve a functional purpose in orienting the urban fabric. However, bending, paint flaking, and deformation were observed in most of the fence elements. Although they feature aesthetically repetitive motifs, they do not convey a unique local identity. The physical boundary elements, such as parking stones and short fixed barriers, used to separate pedestrian and vehicle traffic, are scattered throughout the area. Some parking stones are broken or displaced, while others have lost their function. As they are not sufficiently fixed on the surface, some situations may pose an accident risk. Illuminated delimitation elements integrated with the paving are intended to provide visual

orientation. However, some elements are broken or non-functional, while others are entirely obscured by the ground and are not visible (Figure 6).

Although the delimitation elements on Gures Street partially fulfill their basic functions, they fall short of aesthetic continuity and a holistic design approach. Although these delimitation elements are sufficient in terms of both aesthetics and functionality, they do not offer a unique identity element. The wide variety of designs along the street creates a confusion of perception and design.

3.5. Floor coverings

In floor coverings, a monotonous and straightforward pattern understanding in grey tones has been adopted. This situation does not create visual saturation for users, resulting in an impression of a lack of diversity in urban aesthetics. Although the current use of floor coverings on Gures Street shows partial success in terms of functionality, it has deficiencies in terms of aesthetics, integrity, and reflection of identity. Although the choice of color and texture creates a neutral and simple urban appearance, it is limited in its ability to reflect the local identity. A holistic design relationship has not been established between floor coverings and urban furniture in terms of color, texture, material, and form. For example, benches and waste bins are typically made of dark brown wood and grey metal; however, the aesthetic relationship between these elements and the ground is relatively weak. The lack of harmony between the ground design and urban furniture weakens the spatial integrity of the street and negatively affects the user experience (Figure 7).

3.6. Artistic objects

The clock tower was included as an artistic object, and two clock towers of the same model were identified in the study area. Although the clock tower located on Gures Street attracts attention with its modern and simple design, it is evaluated as an urban object that fails to integrate with the city's identity and establish an aesthetic and functional connection with its surroundings. Although this clock, which forms a dominant vertical element in the space with its steel structure and height, is functional in terms of orientation and time tracking, it lacks an identity value because it does not incorporate motifs, materials, or narratives that reflect the local culture. Visual and spatial harmony could not be established with the electricity panel, benches, and pavement arrangements around the clock; this situation indicates that the elements were placed in a detached and unplanned manner. Considering that symbolic objects in public spaces should be integrated with the environment not only physically but also semantically and contextually, the clock tower example emphasizes the importance of coordinating aesthetics, function, and identity in urban design (Figure 8).

3.7. Water elements

The ornamental fountains and the dry pool area on Gures Street show both functional and aesthetic inadequacies. Most of the fountains are out of use, the water flow has been cut off, and some of them are physically damaged. Although these fountains, designed in the Ottoman style, attempt to reflect the aesthetic understanding of the past with their ornamental details, decorative elements have been obscured due to a lack of maintenance. Rusting, breakage, and contamination have been observed on metal and stone surfaces. This situation both negatively affects the user experience and causes loss of urban aesthetic value (Figure 9).

In addition, the dry pool, also known as the fountain pool, located on the street, is only open during the summer months and cannot contribute to the spatial composition of the street due to its non-functionality at other times and its grey concrete coating, which falls short of visual integrity. This area, which lacks a connection to its surroundings, is perceived as empty and idle ground, drawing attention to its design and functional deficiencies. It is essential to redesign such areas in a manner that not only adds aesthetic value but also has the potential for social use (Figure 10).

3.8. Under-tree gratings and guards

In theory, the cast metal tree gratings used on Gures Street are intended to provide both protection and aesthetic contribution. However, field observations show that these elements have largely lost their function. Due to the deterioration of the soil structure, the uncontrolled growth of weeds, and a lack of maintenance, the gratings present an aesthetically unpleasant, disorganized, and neglected appearance. It has been determined that some of the grates are almost entirely covered with soil, while in others, the gaps between the grates remain dysfunctional. No design elements or motifs reflecting the city's identity were observed in the designs (Figure 11).

Figure 5. Waste bins and their general locations in the study area on Gures Street


Figure 6. Types of boundary elements located in the study area on Gures Street

Figure 7. Paving materials used in the study area on Gures Street

Figure 8. Clocks (art objects) in the Gures Street research area

Figure 9. Fountain elements in the Gures Street research area

Figure 10. Dry pool located in the research area of Gures Street


Figure 11. Under-tree grid elements in the Gures Street research area

3.9. Bicycle parking elements

Although the bicycle parking areas on Gures Street are placed to fulfil specific functions as urban furniture, they display a very inadequate stance in terms of identity and aesthetics. Although the bicycle parks in the visuals evoke industrial, simple, and universal designs in terms of form, they do not incorporate an original design approach that integrates with Siirt's urban identity. No relation is established with the local texture, cultural symbols, or aesthetic references of the region; therefore, these elements are perceived as functional objects brought from outside, rather than site-specific.

From an aesthetic point of view, the intensive use of metal materials, rusting, paint flaking, and deformations on the surfaces indicate that these elements are far from visually intact and poorly maintained. It is observed that some bicycle parks are not integrated with the ground, cannot establish a visual connection with landscaping, and therefore create an adverse visual effect in space. At the same time, the fact that some elements are bent or broken leaves a negative impression both in terms of safety and aesthetics (Figure 12).


Figure 12. Bicycle parking elements in the research area of Gures Street

The evaluation of urban furniture in terms of aesthetics and identity is given in Table 1. In general, the furniture arrangements on the street face a problem of standardization that overlooks the cultural context (Table 1).

Although the urban furniture on Siirt Gures Street generally meets the functional requirements, it shows significant deficiencies in terms of aesthetic continuity and integration with the urban identity. Basic elements, such as seating units, waste bins, boundary elements, and lighting units, are placed with a modern yet anonymous design approach; however, integrity with the local texture could not be established. Although there is symbolic potential in artistic objects such as water elements and clocks, this potential cannot be adequately reflected in the design

integrity. Floor coverings are inadequate both aesthetically and technically, creating a floor perception that falls short of visual harmony with the furniture. Auxiliary units, such as bicycle parking areas, tree grates, and boundary elements, are often deformed, poorly maintained, and lack visual continuity.

Table 1. Evaluation of Siirt Gures Street urban furniture in terms of aesthetics and identity

Type of Urban Furniture	Aesthetic Evaluation	Relation to Urban Identity
Seating Units	Functional and straightforward, a lack of shade, modern yet ordinary	No emphasis on local identity, anonymous design
Lighting Elements	Modern design, uneven light distribution, functional	No local motifs, follow a general modern pattern
Waste Bins	Wooden cladding adds aesthetic value, but placement is inconsistent	Does not reflect urban identity
Boundary Elements (Fences, Borders)	Functional but aesthetically weak	Fails to provide unity with urban identity
Pavement Materials	The ordinary appearance, lack of originality, visible cracks, and uneven surfaces are apparent.	No representation of local symbols or textures
Artistic Objects (Clock Tower)	Modern aesthetics, not integrated with surroundings, and the symbolic potential is not utilized.	Provides aesthetic value but lacks a symbolic connection to identity
Water Features (Decorative Fountains)	Ottoman-style motifs are present, but there is a lack of maintenance and functionality.	Symbolic links exist, but aesthetic issues reduce their identity value.
Tree Grates	Partially aesthetic, but neglected and covered with soil	Weak visual identity, insufficient uniqueness
Bicycle Parking Elements	Functional but lacking visual coherence, signs of damage	Weak identity relationship, design disconnected from local context

4. DISCUSSION AND CONCLUSIONS

Urban furniture, which directly impacts the user experience of public open spaces, is evaluated not only in terms of functionality but also with respect to its aesthetic value and contribution to urban identity (Carmona, 2021). It strengthens the visual identity and aesthetic quality of the city (Grabiec et al., 2022). Properly designed furniture enhances the attractiveness of urban areas and contributes positively to the city's image (Yücel, 2006; Yilmaz et al., 2013; Radwan and Morsy, 2016). However, analyses conducted in this study reveal that the furniture elements on Siirt Gures Street primarily serve functional purposes but are insufficient in establishing a connection with aesthetic continuity and local identity.

Balancing aesthetics and functionality in urban furniture design is crucial for both user experience and the attractiveness of public spaces. Yet, the seating units, lighting elements, and garbage bins on Gures Street are designed in simple, anonymous, and repetitive forms; they are arranged in a way that compromises visual integrity and do not incorporate local materials or motifs. This situation weakens the aesthetic identity of the public space, making it difficult for users to develop a sense of belonging (Stathopoulos et al., 2004; Catalyurekoglu and Altiparmakogullari, 2023). Arruda et al. (2017) emphasize that the design of urban furniture

involves “material shaping” that represents the city’s identity. However, no motifs or symbols specific to Siirt are observed on the benches, lighting, or garbage bins along Gures Street.

Tan and Bayezit’s (2023) study on Siirt Gures Street examine the street’s relationship with urban identity in the context of socio-spatial transformation and public representation. Their study highlights the significance of Gures Street as an axis that shapes urban memory during modernization. However, it pays limited attention to micro-scale design components such as urban furniture. In this article, the role of urban identity is analyzed through the functional and symbolic values of urban furniture, particularly in relation to aesthetic and visual continuity. The macro-scale spatial interpretations presented by Tan and Bayezit (2023) align with the micro-scale aesthetic evaluations of this study, demonstrating that urban identity should be approached holistically, encompassing both physical settlement and equipment elements.

The integration of urban furniture with local identity is essential for ensuring cultural continuity. Nevertheless, symbolic elements with strong potential (such as the clock tower and ornamental fountain on Gures Street) remain disconnected from the urban fabric due to design incompatibility, lack of maintenance, and spatial discontinuity. Contemporary studies underline that symbolic components significantly contribute to spatial identity through visual perception, memory, and meaning-making processes (Toy et al., 2007; Arruda et al., 2017; Bolkaner et al., 2019; Grabiec et al., 2022).

The urban furniture on Gures Street lacks symbolic character and instead reflects globalized design templates, a condition that corresponds to Relph’s concept of placelessness (1976). As a result, the furniture could be found anywhere, without establishing meaningful connections with the place. Kevin Lynch (1960), in his theory of city imageability, argued that urban spaces become “legible” only when designed with consistent and locally specific elements. Although the furniture on Gures Street demonstrates a coherent visual language in terms of design, it lacks the local identity elements necessary for fostering a stronger sense of place (Dogan, 2024).

According to the literature, achieving legibility and a sense of place requires aligning design components with local cultural values (Lynch, 1960; Carmona, 2021). However, findings from this study indicate that while the urban furniture along Gures Street adopts a modern aesthetic, it falls short in reflecting local cultural identity. Trash bins, benches, lighting elements, and pavement materials exhibit standardized modern designs but fail to convey the historical or cultural characteristics of Siirt.

The analysis of urban furniture in terms of aesthetics and identity along Gures Street in Siirt has revealed that, although the existing elements follow functional and widely accepted modern design styles, they lack symbols that reflect the unique identity of Siirt. While the urban furniture generally exhibits contemporary lines, it fails to integrate with the local context, cultural traces, or symbolic meanings. Additionally, several components in active use, such as fountains, bicycle racks, boundary elements, trash bins, and seating units, suffer from serious maintenance issues and physical deterioration, which negatively impact both the user experience and spatial aesthetics. This study recommends incorporating elements that emphasize Siirt’s urban identity into future design processes.

Accordingly, the following suggestions are proposed:

- A design approach aligned with the city's identity should be prioritized, and original furniture inspired by local culture and geography should be developed.
- To ensure visual continuity, urban furniture should be coordinated with paving materials and green space arrangements.
- Furniture elements that are physically damaged, broken, or no longer functional should be rehabilitated or replaced with new ones.
- All types of urban furniture (including lighting units, seating areas, bicycle racks, and artistic objects) should be re-evaluated to enhance user comfort.
- Inclusive and accessible designs should be adopted to accommodate the diverse needs of various user groups, including children, the elderly, and individuals with disabilities.
- Traditional elements such as water features should be reinterpreted through contemporary design approaches to support cultural continuity.

In conclusion, urban public spaces like Gures Street can serve as carriers of identity only through design decisions that reflect and strengthen that identity. Ensuring that urban furniture is not only functional but also compatible with the city in aesthetic, cultural, and symbolic terms will enhance urban livability and increase user satisfaction.

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ASPHALT BINDER MODIFICATION IN FLEXIBLE PAVEMENT USING DIFFERENT AMOUNTS OF CRUMB RUBBER

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Abstract: Every year, thousands of tires made of crumb rubber are consumed as scrap. By burning this material, more landfill space is needed, which poses a health risk and environmental problem. The study concentrated on using crumb rubber in PG76 performance grade and 80–100 penetration grade asphalt binder mix. Using the wet method, the asphalt binders were combined with waste crumb rubber to create a powder form of 40 mesh (0.425 micron). The study focused on replacing 15%, 20%, and 25% of the modified asphalt binder mix's total weight with crumb rubber. The Malaysian JKR/SPJ/2008-S4 standard and the American Society for Testing and Materials (ASTM) served as the foundation for the laboratory work. Numerous tests were carried out, including pressure aging vessel (PAV), rolling thin film oven test (RTFOT), penetration, softening point, and viscosity testing on modified asphalt binder. The outcome demonstrates a beneficial effect, with penetration decreasing as 80–100% and PG76 blend asphalt binder are partially substituted with crumb rubber. In contrast to the 80–100 asphalt binder, the PG76 asphalt binder result exhibits reduced penetration in terms of stiffness throughout both short- and long-term aging. The softening point test results indicate that replacing a portion of the asphalt binder with crumb rubber raises the temperature of the PG76 and 80–100 asphalt binder mix. This is especially true after the PG76 short-term aging test (RTFOT) at 20% replacement, when the temperature reached 85 °C, and after the long-term aging test (PAV), when the temperature dropped to 75 °C.However, resistance to increased temperature susceptibility is indicated by the partial replacement of asphalt binder with crumb rubber. According to the results of the viscosity test, the PG76 asphalt binder is more viscous than the original PG76 and the 80–100 asphalt binder replacement made of crumb rubber mix. For the short-term aging (RTFOT) test, the PG76 asphalt binder suggests that a crumb rubber replacement of 20% is ideal. When compared to the RTFOT test, the viscosity decreased in the long-term aging (PAV) test.

Keywords: Crumb Rubber, Modification, Asphalt Binder Mix, Replacement.

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1. INTRODUCTION

Asphalt binder is characterized by both polar and rheological properties. The main motivation for modifying asphalt binder arises from the limitations of conventional refining methods in producing high-performance binders from crude petroleum oil. Research has shown that modification through advanced refining techniques, chemical reactions, and/or additives can significantly improve the functional properties of asphalt binder and increase its resistance to various forms of pavement deterioration. A recent survey of forty-seven State Highway Agencies in the United States revealed that thirty-five agencies intend to increase their use of modified binders in new road construction. Twelve agencies plan to maintain their current usage levels, while a few indicated a reduction. Premature pavement distresses, particularly fatigue cracking and rutting, were identified by most agencies as the main reasons for adopting modified binders (Bahia et al., 1997)Due to the tremendous chemical complexity of asphalt, conducting a comprehensive chemical investigation is often not feasible (Read and Whiteoak, 2003). Scrap rubber and tires have long been recycled for use in highway and road construction across many Asian, European, and African countries. The incorporation of crumb rubber offers multiple

Benefits: it reduces landfill demand, mitigates environmental impact, and conserves raw materials used in road building. Previous studies (Bahia et al., 1994) have shown that crumb rubber can be incorporated into asphalt binders and paving materials through various mixing and blending techniques, most notably the dry and wet processes. In the dry process, crumb rubber is blended with hot aggregate prior to asphalt addition, whereas in the wet process, crumb rubber is blended directly with asphalt binder before application.Crumb rubber–modified (CRM) asphalt binders generally require higher compaction temperatures compared with conventional mixtures (Amirkhanian and Corley, 2004). Insufficient compaction temperatures can lead to poor volumetric properties, such as excessive air voids, ultimately reducing both short- and long-term pavement performance. Furthermore, the increase in viscosity associated with CRM binders can hinder mixture workability, necessitating elevated compaction temperatures to maintain optimal binder viscosity and ensure satisfactory pavement performance.

1.1 Problem Statement

Urban and highway pavements are typically designed for a service life of 10 to 20 years. However, in practice, pavement deterioration often occurs well before the end of this design life. One of the major contributing factors is the repeated application of heavy traffic loads, which generate tensile strains in the bottom layers of the pavement, ultimately leading to fatigue cracking. Similarly, rutting is a prevalent distress mechanism, particularly in warmer regions such as North Africa and South Asia, where the accumulation of compressive strains at the top of the subgrade layer deforms the pavement surface.To enhance pavement durability and performance, numerous trials have investigated the use of crumb rubber as a modifier in asphalt binders. Incorporating crumb rubber into Hot Mix Asphalt (HMA) not only provides an environmentally responsible solution for recycling industrial waste but also improves the overall efficiency and performance of asphalt mixtures produced in industrial mix plants.

1.2 Objectives of Study

The study's main goal is to partially replace the weight of the blended asphalt binder mix utili zing waste crumb rubber at varied percentages (15, 20, and 25%) through a wet process.The p articular goals are:

1) To assess the physical characteristics of the asphalt binder while using crumb rubber as a partial replacement at different weight percentages (15, 20, and 25%) relative to the total weight of the blended asphalt binder mix.
2) To assess the short- and long-term aging performance of replacing asphalt binder with crumb rubber.
3) To ascertain the ideal percentage of crumb rubber substitution in the asphalt binder mix composition

1.4 Scope of Study

This study focuses on evaluating the physical properties and performance of asphalt binder partially replaced with crumb rubber at varying proportions (15%, 20%, and 25% by total binder weight). Two types of asphalt binders will be examined: performance grade PG-76 and penetration grade 80–100. Multiple sample sets will be prepared, each incorporating different crumb rubber contents and subjected to varied mixing temperatures. All experimental work will be conducted at the Highway and Transportation Laboratory, University Technology Malaysia (UTM), in accordance with the standards specified by the American Society for Testing and Materials (ASTM) and JKR/SPJ/2008-S4. To assess the characteristics of crumb rubber–modified (CRM) asphalt binders, a comprehensive testing program will be implemented. The tests will include viscosity, softening point, penetration, rolling thin film oven (RTFOT), and pressure aging vessel (PAV) evaluations.

1.3 Importance of Research

The creation of a novel, modified asphalt binder including crumb rubber is the study's anticipated result. The CRM asphalt binder is made to reduce pavement costs while improving ride quality. Use crumb rubber in construction in place of certain asphalt binder. Lastly, the development of CRM asphalt binder will contribute to the creation of green and sustainable roads and highways by addressing the issue of industrial waste crumb rubber.

2. LITERATURE REVIEW

2.1 Asphalt Binder

Asphalt, commonly referred to as bitumen, is derived from petroleum oil, which originates from the remains of marine organisms and plant materials deposited on the ocean floor millions of years ago (Whiteoak, 1991). Over time, the immense weight of the overlying sediments compressed the lower layers, while heat from the Earth's crust transformed these organic materials into petroleum. Large subterranean reservoirs are formed when petroleum is trapped beneath impermeable rock layers. Occasionally, faults in the overlying strata allow petroleum to migrate and accumulate near the surface. In modern practice, pile drilling techniques are employed to extract petroleum from subsurface reservoirs (Whiteoak, 1991).Only a small fraction of crude oil is suitable for use as a primary component in asphalt design mixtures. According to British Standard 3690: Part 2 (1989), asphalt is defined as a viscous liquid or solid predominantly composed of hydrocarbons and their derivatives. It may be obtained either from refined crude petroleum oil or as a naturally occurring deposit, sometimes in combination with mineral matter.

2.2 AsphaltBinderModification

Ordinary asphalt is used on most public roads and highways to create well-performing pavements. However, the demand for new roads increases annually due to the growth in automobile traffic. Eventually, these roads face significant problems, the most severe of which are caused by heavy truck loads and extremely high temperatures. Furthermore, because high standards for safety, riding comfort, maintenance frequency, and service life have become critical considerations in road design, it is essential to improve the properties of asphalt binders to enhance performance and reduce pavement distress (Brule, 2007).The ideal binder should maintain low viscosity at typical placement temperatures while exhibiting improved cohesion and minimal temperature susceptibility across the range of service temperatures. Its fatigue resistance, fracture strength, and resistance to permanent deformation should be high, while its sensitivity to loading rate should be minimal. Additionally, it should possess adhesion properties comparable to those of conventional binders. Finally, its aging characteristics should be favorable both during placement and throughout its service life (Brule, 2007).

2.3 Crumb Rubber

The Rubber Manufactures Association reports that a significant number of scrap tires, or crumb rubber, are consumed annually and that these tires are causing grave issues such an increase in landfill area and environmental issues (Snyder, 1998). Using the crumb rubber in the modification of asphalt binders is one of the techniques that have been used in an effort to find more efficient ways to recycle the tires with crumb rubber. According to reports, the up to 40% of crumb rubber can be absorbed by the asphalt industry (Avraam, 2005). Tires are mostly made of rubber, steel, and fiber. Of them, rubber makes up the majority of the tire's composition (around 60% of its weight). Furthermore, the rubber is made up of a variety of substances, including carbon black, various mineral fillers, and natural and synthetic rubbers (Mark et al., 2005). The percentage of natural and synthetic rubber varies between truck and passenger vehicle tires, but overall, ground rubber is rather uniform, and the ground rubber industry is not dependent on any one tire type (Ruth, 1995). The impact of ground tire particle size and grinding technique on asphalt binder qualities was investigated by the National Center of Asphalt Technology (NCAT). Twelve samples of crumb rubber combined with one asphalt binder were used in the study. Twelve mixes containing 10% crumb rubber by weight of asphalt were created, and two further mixes containing 15% rubber were created. According to test results on performance grade, crumb rubber's surface area and particle size had the biggest effects on raising the high-temperature performance grade.

Figure 1. Industrial waste (crumb rubber)

Generally speaking, there are two different processes used to make Crumb Rubber Modified (CRM) binder: wet and dry. Fine CRM and asphalt binder are blended together during the wet

process. Coarse CRM is substituted for aggregate in the asphalt mixture during the dry phase. According to Takallou et al. (1991), the wet procedure is more effective at enhancing the characteristics and functionality of an asphalt mixture. Given its propensity to absorb liquids and swell, crumb rubber is a cheap modifier for asphalt binder that enhances paving performance and safety for the highway pavement sector (Amirkhanian, 2003).

Figure 2. Different sizes of crumb rubber

2.4 Asphalt Rubber

The American Society for Testing and Materials (ASTM) defines asphalt rubber (AR) as "a blend or mix of asphalt binder, reclaimed tire rubber, and certain additives in which the rubber component is at least 15 percent by weight of the total blend and has reacted in the hot asphalt binder." The necessary physical characteristics are outlined in ASTM D 6114, "Standard Specification for Asphalt Rubber Binder," which can be found in Vol. 4.03 of the *Annual Book of ASTM Standards* (2001), as well as in the Caltrans Standard Special Provisions for Asphalt Rubber Binder. To maintain crumb rubber particles in suspension and promote physical interaction between the asphalt binder and rubber constituents, asphalt rubber is manufactured at high agitation temperatures (≥177°C). Different extender oils may also be added to improve workability, facilitate spray applications, and reduce viscosity.The reclaimed rubber, also known as crumb rubber modifier, is made from waste tire rubber. Tire thieves combine natural rubber, synthetic rubber, fillers, carbon black, and oils of the extender kind that dissolve in hot 12 grade asphalt. According to California specifications, asphalt rubber must contain between 18 and 22 percent crumb rubber that has been adjusted by the mix's total mass. Additionally, scrap rubber with a high natural rubber content (25 ± 2 percent by mass) that may come from waste tires or other sources must be included in the CRM.

2.5 Wet Process

There are generally two methods for combining waste crumb rubber and asphalt binder: the wet method and the dry method. Compared to the dry process, the wet method is preferred due to its superior resistance to fatigue and rutting. The wet technique involves mixing asphalt binder with crumb rubber prior to adding heated aggregates (Takallou, 1988). The interaction process depends on several variables, including blending temperature and duration, crumb rubber particle size, quantity and type of mechanical mixing, and the type of asphalt binder. During the wet process, the asphalt binder's aromatic components are incorporated into the polymer network of the natural and synthetic rubber (Heitzman, 1991).

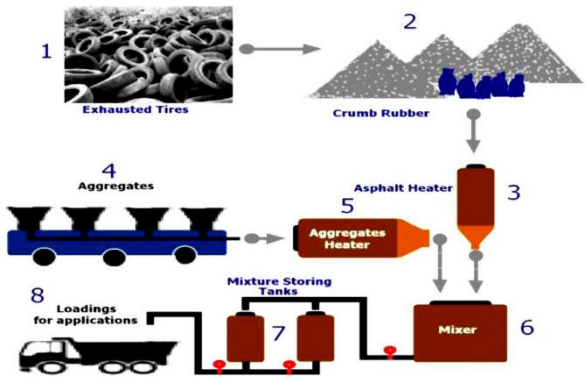


Figure 3. Wet process procedure

2.5.1 Performance of Wet Process

Several researchers have assessed the effectiveness of CRM mixtures produced using the wet technique in both laboratory and field settings. Compared to conventional mixtures, crumb rubber blends produced with the wet method demonstrated superior fatigue resistance in terms of mechanical performance (Harvey et al., 2000; Oliver, 2000). Similar results using the wet technique were observed in dense-graded surface courses, gap-graded surfacing, and binder courses in Louisiana after five to seven years of traffic exposure (Huang et al., 2002). Oliver (2000) also found that the fatigue life of mixtures with 6% or lower binder content was poor and inconsistent. The rut depth of the wet-process mixtures used in Louisiana was equal to or lower than that of the conventional mixtures (Huang et al., 2002).

2.6 Dry Process

In the dry method, heated aggregates and crumb rubber are combined before adding asphalt binder. One dry method, known as Plus Ride, involves adding 1–3% crumb rubber to the mixture, with particle sizes ranging from ½ inch to a No. 10 sieve (Federal Highway Administration, 1998). The air void content, typically between two and four percent, is the primary consideration in the design of the Plus Ride system. Other important variables include the temperature and duration of binder interaction with the ground rubber. These parameters must be carefully controlled to ensure that the ground rubber particles maintain the required stiffness and physical form. Studies conducted in various states have reported mixed results, with some indicating improvements in physical properties and others showing a net economic loss compared to conventional pavement mixtures (Huang et al., 2007).

2.7 Surface Distress Mechanisms: An Overview

Numerous researchers offer explanations for the distress mechanisms of various hot mix asphalts (HMA).The state of the pavement structure that shortens its service life or suitability is called distress. The outward manifestations of various distress processes, which typically result in a decrease in serviceability, are known as distress appearances. Repeatedly high traffic volumes and environmental conditions cause distress. Several distresses can occur on pavement, including rutting, fatigue cracking, delimitation shoving, distortion, raveling, and slippage. These are often caused by strong traffic loads on the pavement surface (Mohamed, 2007).

2.7.1 Permanent Deformation

The accumulation of a tiny quantity of unrecoverable strain brought on by repeatedly applying loads to the pavement results in permanent deformations. Unbound base course, troublesome subgrade, or HMA can all lead to rutting. Consolidation and lateral movement of hot mix

asphalt (HMA) under traffic are the main causes of the persistent deformation in HMA. The top 100 mm of the pavement surface is often where hot mix asphalt (HMA) shear failure happens. But if the right materials aren't employed, it might go deeper (Moha, 2007).

Figure 4. Permanent Deformation (Rutting)

2.7.2 Fatigue Cracking

When strong traffic loads create a horizontal build-up of tensile strain at the bottom of the hot mix asphalt (HMA) layer, fatigue cracking of flexible pavements results. Tensile strain and the permissible number of high load repetitions are related by the failure criterion. The Hot Mix Asphalt (HMA) bottom is where the cracking starts since there is the most tensile strain under wheel load. At first, the cracks spread as one or more longitudinal, parallel fractures. The fractures get joined in a way that mimics an alligator's skin after recurrent strong traffic loads (Mohamed, 2007).

When strong traffic loads create a horizontal build-up of tensile strain at the bottom of the hot mix asphalt (HMA) layer, fatigue cracking of flexible pavements results. Tensile strain and the permissible number of high load repetitions are related by the failure criterion. The Hot Mix Asphalt (HMA) bottom is where the cracking starts since there is the most tensile strain under wheel load. At first, the cracks spread as one or more longitudinal, parallel fractures. The fractures get joined in a way that mimics an alligator's skin after recurrent strong traffic loads (Mohamed, 2007).

Figure 5. Permanent Deformation (Rutting)

2.7.3 Penetration Test

Figure 2.7 illustrates how the concentration of crumb rubber affects the penetration of hot-mix asphalt (HMA). Up to 20% of the total crumb rubber content causes the penetration to decrease. This indicates that the penetration value is significantly influenced by the content of crumb rubber–modified bitumen (CRM). According to Liu et al. (2009), crumb rubber content plays an important role in reducing the penetration value by making the asphalt binder more rigid. This leads to higher resistance to rutting and other forms of permanent deformation. For crumb

rubber concentrations ranging from 4% to 20%, the penetration of the modified binder was reduced on average by 16.5% to 61%. Furthermore, the linear reduction in penetration is illustrated in Figure 2.7, where the correlation coefficient is $R^2 = 0.99$. This behavior is expected because the inclusion of crumb rubber increases the viscosity of the asphalt binder. The effective particle size of the rubber increases with higher crumb rubber content, reducing asphalt penetration due to increased interaction between rubber and asphalt during mixing. Consequently, the rubberized asphalt binder is less susceptible to high temperatures and more resistant to rutting.

2.7.4 Softening Point Test

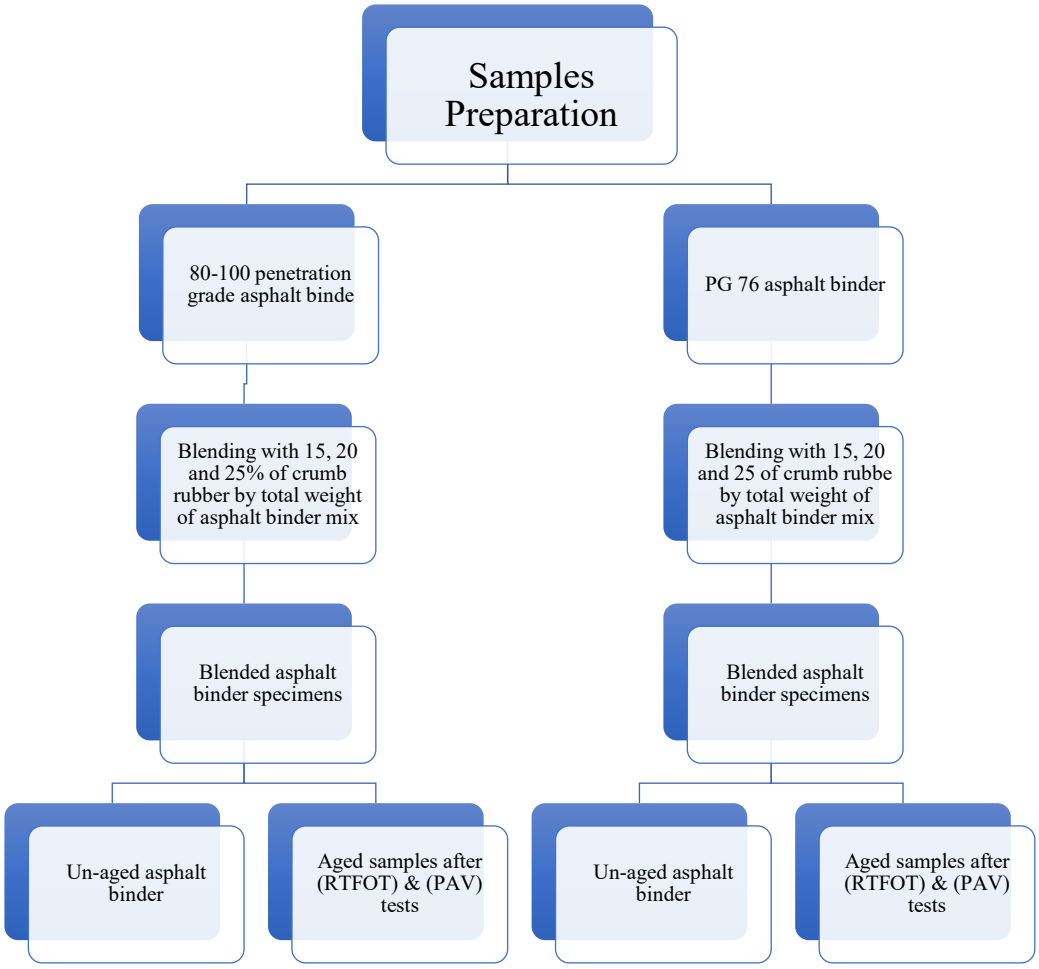
The temperature at which asphalt reaches a specific level of softness is known as the softening point. The softening point increases with higher crumb rubber content when asphalt binder is modified with crumb rubber (Nuha, 2011). The amount of crumb rubber mixed with the asphalt binder affects the characteristics of the blend. Higher rubber content results in significant changes in blend properties, including increases in viscosity, resilience modulus, softening point, and penetration at 25°C. The modified blend also exhibits improved strain values, flexural strength, dynamic stability, and 19–48 h residual stability. Asphalt incorporating rubber particles of 0.2 and 0.4 mm in size produced the best experimental results (Souza and Weissman, 1994).When asphalt and crumb rubber are combined at high temperatures, bitumen components penetrate the rubber, causing it to swell, and interact to form a modified binder during the wet process (Bahia and Davies, 1994). The aromatic oils in the bitumen cause the rubber particles to expand during the initial non-chemical interaction between the asphalt binder and crumb rubber (Heitzman, 1992).

2.7.5 Viscosity Test

Higher crumb rubber content, according to a study, improved the rutting potential qualities and produced more viscosity at 135°C. Additionally, it was noted that higher amounts of fine crumb rubber led to rubberized asphalt binder that had a higher viscosity and a lower resilience modulus (Magar and Nabin, 2014). For every size of crumb rubber and asphalt binder, the ideal crumb rubber content still needs to be ascertained and assessed. The effective physical characteristics and size of the rubber particle are thought to be changed by a physicochemical interaction that takes place between the asphalt and the crumb rubber (Huang et al., 2007). Because of the way that base binders and modified asphalt binder interacted, pavement performance with the use of crumb rubber was superior to that of base binders. The enhancement may result in pavements with a high resistance to rutting (Huang et al., 2007).

3. MATERIAL AND METHOD

This chapter outlines the materials, sample preparation, and testing procedures required to evaluate the performance of crumb rubber–modified (CRM) asphalt binder and achieve the study's objectives. Two types of asphalt binder (AB) are used in this study: performance grade PG76 and penetration grade 80–100. For the 80–100 and PG76 binders, the blending temperatures with crumb rubber are 160°C and 185°C, respectively. In this study, different percentages of crumb rubber (CR) (15%, 20%, and 25%) were used to partially replace the total weight of the asphalt binder mix.The experimental procedures followed the Malaysian JKR standard (JKR/SPJ/2008-S4) and the American Society for Testing and Materials (ASTM), as illustrated in Figure 3.2. The laboratory work includes physical and rheological tests to evaluate the behavior of crumb rubber when used as a partial replacement of the asphalt binder.



3.1 Crumb Rubber Modified (CRM) Asphalt Binder

One provider provided the crumb rubber (CR) used in this investigation. Previous investigations indicated that the lower crumb rubber particle size was experimental work tests physical ASTM D5 Penteration Point; ASTM 4402 Viscosity; ASTM 4402 Rehomological Tests For features of crumb rubber asphalt binder, such as cracking resistance and permanent deformation, RTFOT ASTM 2872 PAV ASTM D454 Result and Data Analysis Conclusion 24 is more effective (Glover and Bullin, 1997). Rubber that had passed through a 40 mesh (0.425 mm) filter was used to create CRM binder, which allowed for inexpensive efficiency and homogenized modification.

Figure 6. Blending Process

Table 1. Test Standard and Equipment

Test Standard	Type of Test	Equipment	Description
ASTM D5	Penetration	Penetrometer	25°C, 100gram, 5 sec
ASTM D36	Softening Point	Ring and Ball	3.5g steel ball, Thermometer for softening temperature
ASTM D 4402	Viscosity	Rotational Viscometer (RV)	135°C and 165°C, spindle 27, 20rpm
ASTM D 2872	Short-term aging	Rolling Thin Film Oven (RTFOT)	163°C for 85min
ASTM D 6521	Long term Aging	Pressure Aging Vessel (PAV)	2.1Mpa for 20 hours

3.2 Penetration Test

The penetration test is regarded as the most traditional physical test for asphalt binder and is used to gauge the consistency of the material. The asphalt binder penetrations measure the centimeters to which a standard needle can pierce the material under constant loading, temperature, and time conditions. The penetration test standard procedure used predetermined conditions, with a fixed temperature of 25°C/75°F, a constant weight of 100g, and a known time of 5 seconds. The test was carried out on both pure and modified asphalt binder with different percentages of crumb rubber (15, 20, and 25%). For instance, the asphalt binder 80-100 penetrations show that the asphalt's range of penetration is 80-100, measured in tenths of a millimeter. A tougher grade of asphalt binder is crucial, as indicated by the lower penetration value.

3.2.1 Procedures of Penetration Test

a) The sample was heated until it melts to pour.
b) The sample was then poured in a specific sample container for penetration test to a depth such that when cooled and kept at room temperature of a test of 25°C.
c) Each container was covered as a protection from dust and allowed it to cool for 1 to 1½ hours for the small container and 1½ to 2 hours for the larger container.
d) The samples were placed in the water bath and maintained the temperature to 25°C for 1 to 1½ hours depending on container choosing.
The penetration needle was cleaned with benzene and dried with a clean cloth.

a) The sample container (100g) was placed directly on the submerged stand in the penetrometer and sample was covered in water bath 25o + 0.5oC.

b) The needle was positioned slowly lowering it until it's just makes contact with the surface of the sample.
c) The pointer of penetrometer was set to zero.

d) The needle holder was released for the specific period of time (5sec) and the distance penetrated was measured in 1/10mm reading.
e) The needle was cleaned after the result was taken.
f) Three determinations were made at points on the surface of the sample not less than 10mm from the side of the container and was obtained the average reading of penetration

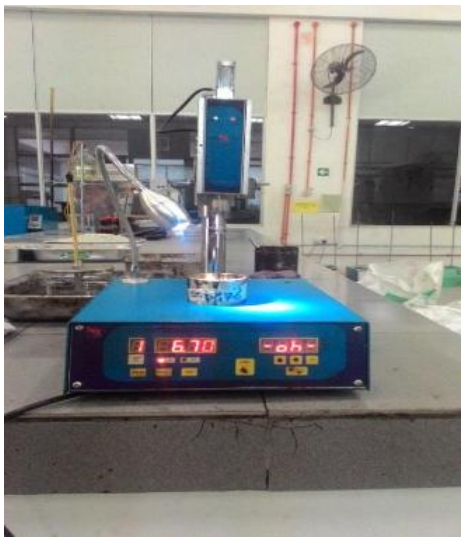


Figure 7. Penetration test setup

3.3 Viscosity Test

Resistance to flow is known as viscosity, and it is a basic property of asphalt binder that governs the material's behavior both at a specific temperature and across a temperature range. The Superpave PG asphalt binder specification test is always carried out at high temperature, which is 329°F (165°C), and at 275°F (135°C). The basic RV test calculates the torque needed to keep a cylindrical spindle submerged in an asphalt binder at a consistent temperature and rotating at a constant speed of 20 revolutions per minute. The RV then automatically converted this torque to a viscosity and presented it. The ASTM D4402 test process was followed in the description that follows.

3.3.1Procedures of Viscosity Test

a) Spindle, sample chamber, and viscometer environmental chamber
(Thermosel) were preheated to (135°C).

b) The unaged and aged asphalt binder were heated until fluid enough to pour. Stir the sample, being careful not to entrap air bubbles.
c) (11g) the weight of asphalt binder was poured into sample chamber; the sample size varies according to the selected spindle (number 27 spindle).

d) Sample chamber was inserted into the rotational viscometer (RV) temperature controller unit and carefully lowered spindle into the sample.

e) The sample was brought to the desired test temperature (typically 275°F) (135°C) within approximately 30 minutes and allows it to equilibrate at test temperature for 10 minutes.

f) The spindle was rotated at 20 RPM, making sure the percent torque was indicated by the RV readout remains between 2 and 98 percent.
g) Once the sample was reached temperature and equilibrated, 3 viscosity readings from RV display were taken, allowing 1 minute between each reading. Viscosity was reported as the average of 3 readings.

Figure 8. Penetration test setup

3.4 Rolling Thin Film Oven Test (RTFOT)

The rolling thin-film oven test (RTFOT) is one of the rheological tests used to examine the behavior of hot mix asphalt (HMA) pavement at early stages, simulating short-term aging of an asphalt binder during the manufacturing or mixing process. The test also measures the mass change in the asphalt binder following the aging process. The RTFOT primarily simulates short-term aging of the asphalt binder during mixing, hauling, and compaction of HMA. Samples tested using RTFOT can subsequently undergo further evaluations, such as the Dynamic Shear Rheometer (DSR) test to measure rutting resistance. This test was conducted in accordance with ASTM D 2872.

3.4.1 Procedures of (RTFOT) Test

a) The sample of asphalt binder sample was heated until fluid or melted.
b) Two RTFOT bottles were labeled and weighed empty and the weights were recorded.
c) The 34.5g weight of asphalt binder was poured into each bottle.

d) The bottles were allowed to cool, after cooling, the two mass changes of bottles were weighed again and recorded the mass loss after the aging.
e) The main switch was turned on and the testing temperature was set at163ºC.

f) Once the temperature was reached 163ºC, the bottles were installed which contain asphalt binder was put into the slot in the oven.
g) The air compressor was turned on and the valve was set at a pressure of 4 bars.

h) The switch labeled "ALARM" was turned on to turn on the motor to spin the bottle in the oven.

i) This testing was completed after 85 minutes.
j) Finally, the test was completed and the pressure was returned to 0 and the air compressor was turned off.
k) The glass bottles were removed one by once carefully and poured the hot asphalt binder into the cup.

Figure 9. Rolling Thin Film Oven Test **(** RTFOT) machine

4. RESULTS AND FINDINGS

4.1 Introduction

This chapter's primary goal is to study and assess the findings from laboratory experiments in which the impact of substituting different percentages of crumb rubber powder for asphalt binder was examined. Physical testing was utilized in the laboratory to ascertain the physical characteristics of the aged and unaged asphalt binder and the crumb rubber modified mix. Viscosity, softening point, and penetration tests are part of the physical test. The rolling thin film oven and pressure aging vessel
Tests are part of the second step of rheological testing.

4.2 Chemical Components of Crumb Rubber

According to the American Society of Testing and Materials, Yong Fong Rubber Industries provided the crumb rubber in powder form (ASTM). The following is a list of chemicals that make up crumb rubber:

Table 2. Chemical components of the crumb rubber powder used in the study (Source: Young Fong Rubber industry)

Chemical Composition	**Values (%)**
Acetone Extract	10 ± 3
Ash Content	4 ± 3
Carbon Black	32 ± 5

4.3 Penetration Properties Results

A penetration test is typically used to determine the consistency of asphalt binder or the depth to which the material is penetrated by an asphalt binder standard needle under established loading, temperature, and time conditions. As an illustration, the asphalt binder penetration value is 90 if the needle penetrates at 9 mm. Based on penetration value, asphalt binder penetration grade is determined. To assess the impact of the crumb rubber powder percentages (15, 20, and 25%), this study will concentrate on two distinct types of asphalt binder penetration grade (80-100) and performance grade PG 76 containing varying percentages of crumb rubber powder. From the result shown in the Table 4.2 and 4.3 the penetration value of 80- 100 binder respectively of unaged asphalts binder of normal and modified asphalt binder with crumb rubber before the short term aging (RTFOT) and long-term aging (PAV) test.

Table 3. Penetration results of penetration grade 80-100 unaged modified asphalt binder

CR %	Test Number 1	Test Number 2	Test Number 3	Average	Overall Average
0	86.20	92.00	82.00	86.73	
0	88.70	86.20	90.50	88.46	85.14
0	78.00	90.50	72.20	80.23	
15	53.00	74.50	60.00	62.50	
15	49.50	51.00	51.70	50.73	55.56
15	53.20	50.50	57.50	53.73	
20	46.70	44.00	47.20	45.90	
20	48.70	52.20	48.70	49.80	46.72
20	43.70	46.70	43.00	44.46	
25	36.70	43.20	42.20	40.70	
25	40.00	43.00	44.00	42.50	43.03
25	42.20	44.70	42.00	42.90	

Based on Figure 4.1 the penetration value for 80-100 and PG76 are reduced, because the crumb rubber has a strong effect of decreasing the penetration value by increasing the stiffness of crumb rubberPowder of asphalt binder mix. The penetration values of performance grade PG76 of asphalt binder in original form and modified with crumb rubber showed the lower result when compared to penetration grade 80-100 asphalt binder. Therefore, it expected the Hot Mix Asphalt (HMA) using PG76 is more resistance to rutting potential compared with 80-100 asphalt binder

4.3 Penetration Properties Results

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4.4 Softening Point Results

The result of softening point or the phase change of temperature of control and modified asphalt binder with crumb rubber before the short-term aging and longterm aging shown in the Tables 4.8 and 4.9 for penetration grade 80 - 100 and performance grade PG76 respectively. Figure 4.4 shows the crumb rubber powder percentage against softening point as the partial replacement of total weight of asphalt binder mix (15, 20, and 25%). The results shows the crumb rubber increasing the softening point of the crumb rubber modified asphalt binder, thus improving the asphalt binder to resist the high-temperature deformation in the road surface.
From Figure 4.5 shown the softening point of performance grade, PG76 indicates strong of temperature change of 61.5oC at 25% replacement compared with penetration grade 80-100 asphalt binder. The increasing of phase change of temperature indicates the asphalt binder more stiffness and hard to resist the effect of higher temperature.

5. DISCUSSION AND CONCLUSIONS

The purpose of the study was to determine how different percentages of crumb rubber powder, which were used to partially replace PG76 and 80-100 in the total weight of the asphalt binder mix, would affect the rheological and physical characteristics of the mixture both before and after aging. The Penetration, softening, rolling thin-film oven, viscosity, and pressure-aging vessel tests are the main emphasis of the examination.

From these tests results, the following conclusions were drawn for the materials used in this study:

i. The increase in percentages with partial replacement of crumb rubber will reduce the percentage value of penetration value for 80- 100 asphalt binder. However, the PG76 asphalt binder shows the lower result of penetration before and after short term and long term aging compared with 80 - 100 asphalt binder in term of stiffness. The optimum percentage of crumb rubber is the 15% as the partial replacement of total weight of asphalt binder after the long term aging.

ii . The softening point results shows that the percentage of replacement of asphalt binder with crumb rubber increased the temperature for penetration grade 80-100 and PG76 asphalt binder mix.

iii. The viscosity results shows that the PG76 asphalt binder replaced with crumb rubber has higher viscosity compared with penetration grade 80-100 asphalt binder replacement with crumb rubber before aging.

The study offers some advice and ideas to enhance the outcome in the future when employing crumb rubber as a partial replacement.

I. When replacing the entire weight of the asphalt binder mix with varying percentages of crumb rubber, research should be done to examine and assess the physical and rheological characteristics of the mixture both before and after the aging process.

II. ii. Greater research should be done to assess the resistance to rutting and fatigue cracking using the Dynamic Shear Rheometer test (DSR). This will provide greater insight into the characteristics of the crumb rubber modified asphalt binder that can be used as a replacement both before and after the aging process.

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Ethics Committee Approval / Etik Kurul Onayı
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Peer-review
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Author Contributions
All work is done as reveiw paper, I have studied a lot of papers and has writen this paper.

Conflict of Interest
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LIFE CYCLE ASSESSMENT IN HISTORIC BUILDINGS: A BIBLIOMETRIC EXPLORATION OF GLOBAL RESEARCH TRENDS

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Abstract: Efforts to mitigate the environmental impact of the construction sector increasingly rely on analytical tools aligned with sustainability principles. Among these, Life Cycle Assessment (LCA) plays a critical role by quantitatively evaluating the environmental effects of buildings across all life stages, thereby informing design and decision-making processes. However, existing literature predominantly focuses on LCA applications in new constructions, while historic buildings—often recognized as cultural heritage assets—remain underrepresented in this context. This study systematically investigates global academic trends in LCA applications within historic buildings through bibliometric analysis. 310 publications indexed in the Web of Science Core Collection between 2001 and 2025 were examined, based on the keywords "historic building" and "life cycle assessment." Bibliometric tools such as VOSviewer and the Bibliometrix R package were employed to visualize keyword co-occurrence, source coupling, and author collaboration networks. Thematic classification was conducted semi-automatically using high-frequency keywords. Findings reveal that topics such as energy efficiency, carbon emissions, adaptive reuse, and sustainable restoration dominate the literature, whereas significant research gaps persist in areas like social sustainability, traditional material data, and policy support. The study aims to contribute to interdisciplinary scholarship by promoting scientifically grounded evaluations of the environmental performance of historic buildings and advancing sustainable conservation strategies.

Keywords: Life cycle assessment (LCA), Historic buildings, Sustainable conservation, Bibliometric analysis, Cultural heritage, Environmental impact.

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1. INTRODUCTION

The construction sector stands out as one of the areas with the highest environmental impact worldwide in terms of greenhouse gas emissions, energy consumption, and natural resource use (Potrč Obrecht et al., 2020; Dsilva et al., 2023). Therefore, the quantitative evaluation of buildings' environmental performance in line with sustainability principles is of great importance for both design and conservation processes. In this context, Life Cycle Assessment (LCA) is widely employed as a scientific method that enables a comprehensive analysis of the environmental impacts generated across all life stages of a building—from raw material acquisition to end-of-life disposal (Bjørn et al., 2018; van der Giesen et al., 2020).

In recent years, LCA has increasingly served as an effective decision-support tool, particularly in areas such as material selection, energy-efficient design, and the development of circular economy strategies. It also plays significant roles in promoting sustainable design, supporting certification processes, and informing policymaking (Najjar et al., 2019; Marsh et al., 2023; Kumar et al., 2025). However, common applications of this method tend to focus primarily on new construction projects, while heritage buildings of cultural significance remain relatively underrepresented in the literature (Franzoni et al., 2020; Mahmad et al., 2024).

Yet, interventions such as the restoration, adaptive reuse, and maintenance of historic buildings have considerable environmental implications due to their high embodied carbon content and extended service lives (Hu & Świerzawskib, 2024). Compared to demolition and reconstruction scenarios, conservation-oriented strategies often demonstrate lower environmental impact levels within the scope of LCA, thereby highlighting the need for hybrid models that simultaneously address both cultural and environmental sustainability goals (Karoglou et al., 2019; Endo & Takamura, 2021). Nonetheless, the lack of data on traditional construction materials, the difficulty of quantifying cultural values, and the absence of standardized methods currently limit the scope of such analyses (Bonoli & Franzoni, 2019; Fnais et al., 2022).

Against this backdrop, a systematic examination of the existing academic literature on the life cycle assessment of historic buildings is required. The primary aim of this study is to analyze relevant academic publications indexed in the Web of Science (WoS) database between 2001 and 2025 using bibliometric analysis methods, in order to identify research trends, thematic clusters, and methodological orientations in the field. The study employs visual and quantitative analytical techniques such as keyword co-occurrence mapping, source citation networks, and Sustainable Development Goal (SDG) matching (Donthu et al., 2021). In doing so, it seeks not only to reveal the current focal areas in the literature but also to identify themes that have not yet been sufficiently explored.

Within the scope of this study, the following objectives were pursued:

- To identify the key concepts and themes highlighted in the literature on historic buildings within the context of LCA,
- To determine the research areas that have received the most attention as well as those that have been neglected,
- To classify the methods, datasets, and assessment tools employed,
- To identify research gaps that could contribute to sustainable conservation strategies,
- To provide guiding recommendations for future scholarly research.

In this regard, the study offers a scientific basis for conservation strategies that address both environmental and cultural sustainability, while simultaneously creating a strategic literature map for policymakers, researchers, and practitioners in the field of life cycle assessment.

2. CONCEPTUAL BACKGROUND

LCA is a scientific, quantitative method for evaluating the environmental impacts of products, services, or systems throughout their life cycle—from raw material extraction to final disposal. It is widely applied across sectors to enhance sustainability, compare alternatives, and support decision-making (Bjørn et al., 2018; van der Giesen et al., 2020). By taking a holistic view of all life stages, LCA uses scientific methods and data to quantitatively reveal environmental impacts.

A key feature of LCA is its "cradle-to-grave" scope, covering raw material extraction, production, use, and end-of-life disposal. This comprehensive, science-based approach evaluates impacts using quantitative data. Figure 1 shows the main processes of LCA and their cyclical progression.

By addressing multiple environmental aspects—such as carbon footprint, resource use, and pollution—LCA supports both retrospective (ex-post) and forward-looking (ex-ante) analyses (Bjørn et al., 2018; Buyle et al., 2019; van der Giesen et al., 2020).

As a decision-support tool, LCA helps compare alternatives and identify "hotspots" at the product, process, and system levels, guiding improvements toward sustainability goals (Bjørn et al., 2018; Christensen et al., 2020; Potrč Obrecht et al., 2020). It is used not only in the private sector but also in environmental certification, regulatory compliance, and public policy development (Batal, 2019; Christensen et al., 2020). With applications in waste management, wastewater treatment, construction, technology, and policy-making, LCA has become essential for assessing environmental impacts and supporting multi-sectoral sustainability efforts.

LCA is a key tool for assessing and reducing the environmental impacts of the construction sector, which significantly contributes to global emissions and resource use. It guides sustainable design, material selection, and policy development. Early-stage integration allows architects and engineers to compare alternatives, identify environmental "hotspots," and make data-driven choices, especially when combined with tools like BIM (Potrč Obrecht et al., 2020; Kumar et al., 2025).

Applications in projects, such as a Dubai case achieving a 26% reduction in embodied carbon, show its potential (Dsilva et al., 2023). LCA supports green certifications like BREEAM and LEED, drives the preparation of EPDs, and promotes circular economy practices (Marsh et al., 2023). Hybrid LCA methods offer broader results but face transparency and standardization challenges (Bakindi et al., 2025). Improving data quality and addressing uncertainties is critical for reliable outcomes (Resch et al., 2021). Overall, LCA is indispensable for minimizing the environmental footprint of the built environment and advancing sustainability goals.

2.2. Types and Focus Areas of LCA

Key life cycle–based frameworks for assessing sustainability include Life Cycle Assessment (LCA), Life Cycle Costing (LCC), Social Life Cycle Assessment (sLCA), and Life Cycle Sustainability Assessment (LCSA). Each focuses on a different sustainability dimension: LCA

on environmental impacts, LCC on economic costs, and sLCA on social effects such as working conditions and stakeholder impacts (Sala et al., 2013; Guinée, 2016; Nubi et al., 2024; Konaré et al., 2023; Furness et al., 2021; Przytuła & Burchart, 2024; Schau et al., 2012; Venkatesh, 2018).

While these methods can be applied separately, LCSA integrates all three to provide a comprehensive assessment of environmental, economic, and social performance (Sala et al., 2013; Guinée, 2016; Nubi et al., 2024; Konaré et al., 2023; Furness et al., 2021; Przytuła & Burchart, 2024; Schau et al., 2012; Hu et al., 2013). Table 1 summarizes their main focus areas.

Table 1. Types and differences of LCA derivatives (Created by the author)

Framework	Main Focus	Dimension Assessed	Integration Level
LCA	Environmental	Environmental impacts	Single
LCC	Economic	Costs	Single
sLCA	Social	Social impacts	Single
LCSA	Holistic	All three (Econ, Env, Soc)	Integrated

LCA is increasingly used to assess and reduce the environmental impacts of historic buildings, guiding sustainable restoration, adaptive reuse, and maintenance strategies. It enables comparison of operational and embodied impacts across restoration methods, helping identify solutions with the lowest footprint (Bonoli & Franzoni, 2019; Franzoni et al., 2020; Endo & Takamura, 2021).

Adaptive reuse projects generally show significantly lower environmental impacts than demolition and new construction, highlighting the importance of reuse in heritage conservation (Hu & Świerzawskib, 2024). LCA is particularly valuable for embodied carbon assessments in maintenance and repair, where intervention durability and end-of-life scenarios are critical (Franzoni et al., 2020; Mahmad et al., 2024).

Challenges include limited data on traditional materials, difficulty balancing cultural preservation with environmental goals, and lack of standardized methods and policy support (Bonoli & Franzoni, 2019; Karoglou et al., 2019; Franzoni et al., 2020; Endo & Takamura, 2021; Fnais et al., 2022; Hu & Świerzawskib, 2024; Mahmad et al., 2024). Overall, LCA supports informed decision-making in heritage interventions, but its effectiveness depends on better material data, stronger integration with cultural priorities, and improved policy frameworks.

3. MATERIAL AND METHOD

This study adopts a bibliometric analysis approach to examine the development and research trends of academic publications on LCA in historic buildings. As a multidisciplinary research field, LCA has broad applications spanning both architectural and engineering domains. However, this diversity has resulted in a scattered and rapidly evolving body of literature. In this context, bibliometric analysis is chosen as a suitable and comprehensive method to systematically map the accumulated knowledge, identify existing research clusters, and reveal potential gaps in the field.

Bibliometric analysis enables the quantitative evaluation of scientific publications on a given topic. This method offers an effective framework for tracking the evolution of literature over time, visualizing relationships among subject areas, and uncovering academic collaborations (Donthu et al., 2021). Additionally, it holds value for interpreting the field's development and providing strategic guidance for future research.

Accordingly, a search was conducted in the Web of Science (WoS) Core Collection database using the keywords ("historical" OR "historic" OR "renovation") AND ("life cycle assessment" OR "LCA"). The retrieved publications were limited to the categories of construction technologies, green and sustainable technologies, environmental engineering, and civil engineering. The search resulted in 310 English-language academic articles; book chapters, conference proceedings, abstracts, and other document types were excluded from the analysis.

The dataset underwent a two-stage analysis process. In the first stage, publications were examined according to the following criteria:

- Publication trends over the years.

In the second stage, the analyzed data were visualized using VOSviewer software, and the following bibliometric relationships were evaluated:

- Keyword co-occurrence analysis,
- Bibliographic coupling (co-citation) analysis.

Through these analyses, the thematic distribution of LCA research in historic buildings, academic collaborations, and leading researchers in the field were revealed, aiming to provide a comprehensive mapping of the domain.

The distribution of publications by year indicates a marked increase in academic interest in LCA related to historic buildings, particularly after 2015. While the number of publications was quite limited between 2001 and 2011, it rapidly rose from 2019 onwards, peaking at 46 publications in 2024 (Figure 1). This growth reflects the increasing importance of the LCA approach within sustainability and heritage conservation fields. The lower count for 2025 may be due to the year not being complete at the time of data collection.

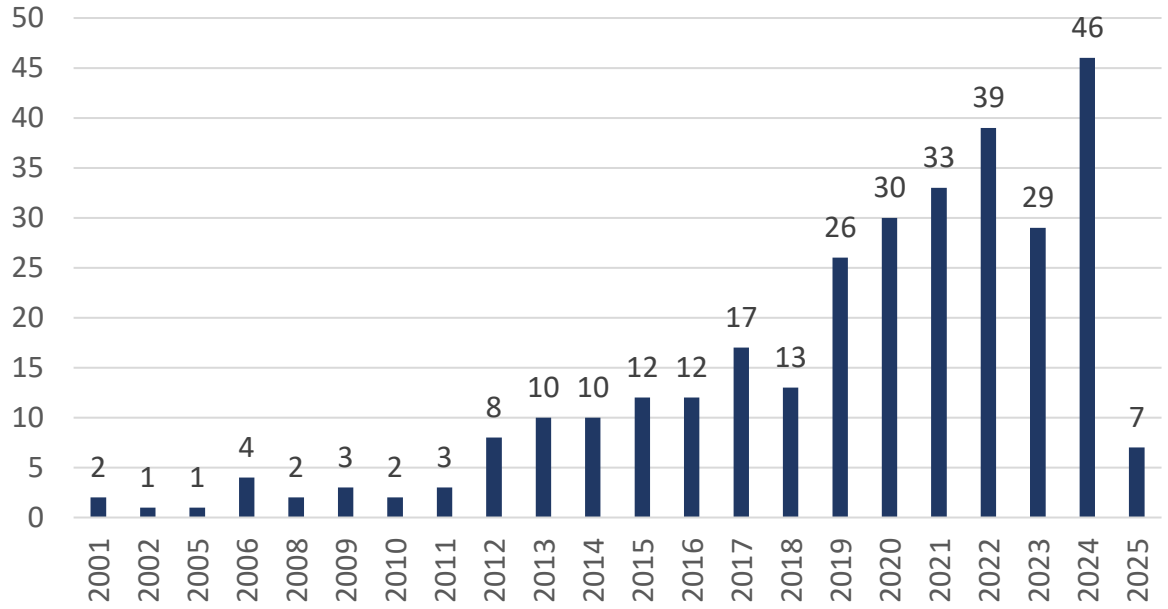

Figure 1. Publication distribution by year

The co-occurrence network of keywords in LCA publications on historic buildings from 2001 to 2025 reveals the main research trends and thematic clusters in the literature. Constructed using VOSviewer software, the term “life cycle assessment” occupies a central position in the network, with a high number of connections indicating that it constitutes a core conceptual node in the field. Variations in the term’s spelling appear as separate nodes within the network, reflecting the terminological diversity present in the discipline (Figure 2).

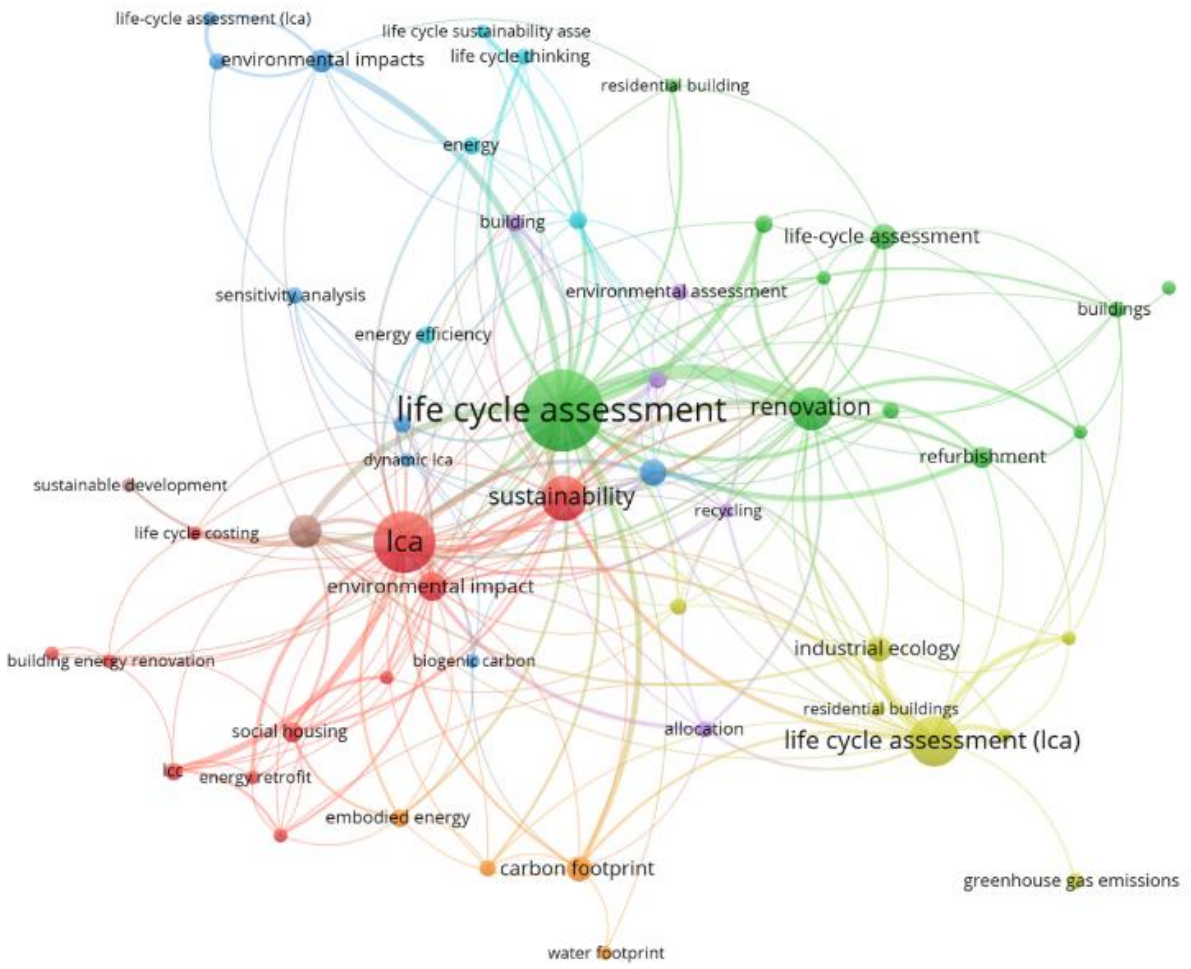

Figure 2. Keyword co-occurrence network of publications

The keywords located at the center of the network are the most frequently used terms and those most strongly connected to other concepts. The colors represent distinct clusters, each grouping keywords that are more closely related within themselves. Specifically:

- The green cluster includes terms such as life cycle assessment, renovation, building, and refurbishment, representing LCA studies primarily focused on building renovation and rehabilitation processes.
- The red cluster comprises keywords like LCA, environmental impact, life cycle costing, sustainable development, and energy retrofit, encompassing studies centered on environmental impacts and cost analyses.
- The yellow cluster contains concepts such as carbon footprint, industrial ecology, and greenhouse gas emissions, reflecting research focused on carbon footprint and industrial processes.
- The blue cluster includes environmental impacts, sensitivity analysis, and energy efficiency, representing more analytical and performance-measurement-based studies.

The connecting lines in the network indicate the frequency with which two keywords are used together. As the thickness of the lines increases, so does the co-occurrence intensity of the two terms in the literature. Additionally, the size of the nodes represents the usage frequency of each keyword. For example, the term life cycle assessment is depicted by the largest node, highlighting it as the most frequently used keyword.

Overall, the findings reveal that the literature on life cycle assessment primarily concentrates around several key themes: building renovation and rehabilitation processes, environmental impact and cost analysis, sustainability and carbon footprint issues, as well as energy efficiency and performance evaluations. The concepts of life cycle assessment and sustainability form a common axis across all clusters, indicating the adoption of an interdisciplinary approach.

The cluster and density network of co-cited references based on publications in the field of LCA for historic buildings between 2001 and 2025 illustrates the usage patterns of sources frequently cited together (Figure 3). This visualization, generated using VOSviewer software, highlights the sources that are often co-cited within the literature.

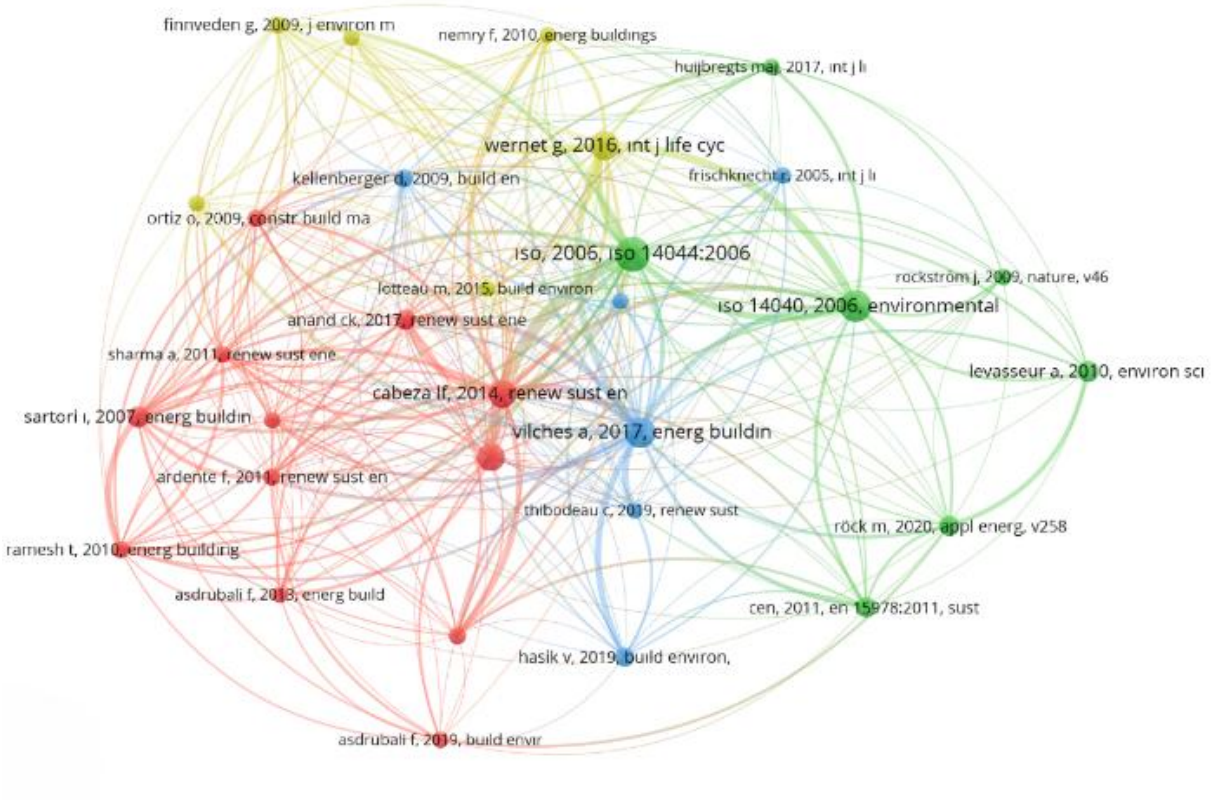

Figure 3. Clustering and density of co-cited references in publications

The resulting co-citation network illustrates that the literature on life cycle analysis of historic buildings is shaped by diverse interdisciplinary approaches. The clusters in the visualization represent different knowledge domains based on both environmental impact assessment methodologies and sustainability practices at the building scale:

- The red cluster includes sources focusing primarily on building-scale energy efficiency, renovation, and sustainability strategies. Authors such as Cabeza et al. (2014) and Vilches et al. (2017) stand out in this cluster with studies assessing the performance of existing building stocks and proposing improvement measures. This cluster is particularly valuable for research on energy retrofitting and adaptive reuse potential of historic buildings.
- The green cluster encompasses the theoretical foundations of LCA alongside standardized environmental assessment frameworks. References such as ISO 14040:2006, ISO 14044:2006, and Rockström et al. (2009) provide the methodological framework enabling the evaluation of historic buildings' environmental performance according to universal criteria.
- The blue cluster highlights applied aspects of life cycle analysis, consisting of

publications featuring detailed comparative studies of building materials. Works by Hasik (2019) and Cen (2011) are frequently cited in material-based comparative analyses, such as those contrasting reinforced concrete with traditional historic building materials.

- The yellow cluster reflects methodological literature addressing more theoretical, conceptual, and scope-defining aspects of LCA. Authors like Finnveden et al. (2009) are especially important in ensuring methodological coherence in LCA scenarios applied to historic building adaptive reuse or preservation processes.

The strong interconnections among all these clusters indicate that LCA functions not only as a technical analytical tool but also as an interdisciplinary evaluation framework. In the processes of preservation, adaptation, and sustainable transformation of historic buildings, the LCA approach offers a holistic perspective that simultaneously considers both environmental and cultural sustainability.

4. RESULTS AND EVALUATION

This bibliometric analysis examined the thematic orientation, geographic distribution, and core source clusters of scientific publications on Life Cycle Assessment (LCA) in historic buildings.

Findings show a notable rise in academic interest after 2015, with rapid growth after 2019. The number of publications reached 46 in 2024, underscoring the growing importance of evaluating historic buildings within the sustainability context.

Italy and the United States lead in publication output, followed by China, Spain, Belgium, and France. This reflects Europe's strong heritage conservation tradition and the increasing sustainability-driven construction activities in the US and China.

Keyword co-occurrence analysis identifies four main research axes: (i) building renovation and rehabilitation, (ii) environmental impact and cost analysis, (iii) carbon footprint and emission management, and (iv) energy efficiency and performance measurement. The consistent linkage between "Life Cycle Assessment" and "sustainability" across clusters highlights the interdisciplinary and multifaceted nature of the field.

The co-citation network reveals four major literature clusters: energy efficiency and sustainable building performance, environmental assessment methodologies, material-based comparative applications, and conceptual LCA approaches. Dense interconnections among sources indicate a maturing body of literature with emerging standard references.

5. DISCUSSION AND CONCLUSIONS

This study systematically reviewed academic literature on Life Cycle Assessment (LCA) in historic buildings, identifying current trends, thematic focuses, and development potentials. Findings show that LCA is increasingly applied beyond new construction to guide sustainable restoration, adaptive reuse, and maintenance of historic structures.

Bibliometric analysis reveals a sharp rise in studies in recent years, concentrated mainly in Europe and in countries such as the United States with large building stocks. Keyword and source analyses indicate a strong emphasis on technical aspects—environmental impacts, energy efficiency, and carbon footprint—while social sustainability and the quantification of cultural values remain underexplored.

Methodological and data-related challenges hinder full integration of LCA in historic contexts. Key issues include the lack of specific data on traditional materials, difficulty translating cultural priorities into quantitative models, and limited policy support. These gaps restrict the ability to balance heritage conservation with sustainability goals.

To achieve a more holistic sustainability approach, future LCA applications in historic buildings must incorporate environmental, social, and economic dimensions. Strengthening interdisciplinary collaboration and enhancing data integration through digital tools will be critical to advancing sustainable preservation of the historic environment.

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A NEW APPROACH FOR RISK ASSESSMENT: THE CARTESIAN PRODUCT METHOD

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Abstract: In this study, a new risk scoring method, the Cartesian product method, is proposed. While existing risk scoring methods accept a single value for probability and severity parameters, the proposed method accepts a range for both probability and severity parameters for the risk related to the identified hazard source. The importance of the Cartesian product method is demonstrated by a real application study and compared with matrix and Fine-Kinney methods. Furthermore, a cloud software called CPMRisk is designed for easy understanding and application of the method.

Keywords: Fine-Kinney, Risk scoring, Hazard, Occupational health and safety.

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1. INTRODUCTION

Businesses have legal regulations to comply with in order to provide a safer working environment. Ensuring that production is carried out under safe conditions is the subject of occupational health and safety. According to the Occupational Health and Safety Law No. 6331 (Occupational Health and Safety Law, 2012), risk assessment has been made mandatory for employers to identify and eliminate hazards that exist in the workplace. In accordance with the relevant regulation, it is obligatory to periodically renew the risk assessment studies according to the hazard class of the workplace (Oturakçı and Dağsuyu, 2017). If the risk cannot be eliminated, it should be controlled.

Although there are many risk scoring methods, one of the most commonly used methods is the Fine-Kinney (FK) method (Oturakcı and Dagsuyu, 2017). The main three parameters used in risk scoring by FK method are probability, severity and frequency (Kinney and Wiruth, 1976). The determination of these parameters is entirely under the control of the expert performing the relevant risk scoring. The occupational health and safety expert does not have any tools and data sources to use when determining the relevant parameters. The expert tries to estimate the relevant parameters based on the observations. Therefore, the risk rating for the same hazard source varies from expert to expert. The main reason for the difference is the

lack of a standardized approach in determining the probability and severity parameters. Additionally, it is often not possible to accept a single point value for the risk scoring parameters.

Risk assessment involves examining the risks posed by identified hazards. Risk assessment is a two-stage process. In the first stage, a scoring is made with the appropriate method for the identified risk. In the second stage, control measures to be taken according to the degree of risk are determined.

Aker and Özçelik (2020) applied the matrix method and the FK methods for a company operating in the metal sector and showed that the risk analysis performed by FK method produces more reliable results than the matrix method. Erzurumluoğlu et al. (2015) carried out risk analysis for tower crane lifting activities according to FK method and made necessary recommendations to reduce the risks that may be caused by hazards to an acceptable level. Cündübeyoğlu and Kayabaşı (2022) conducted a risk assessment in a ceramic factory using the FK method and determined the necessary corrective/preventive actions to reduce high risks to acceptable levels. Durmuş et al. (2021) performed a risk assessment study for a tea factory with FMEA and FK methods. Yorulmaz and Sezen (2023) examined the risk assessment for the maritime field and stated that only the use of the FK method is insufficient, therefore it is appropriate to use it together with other methods.

More sophisticated methods have been introduced by the researchers. Kokangül et al. (2017) developed a hybrid risk assessment approach by combining the Analytic Hierarchy Process (AHP) with the FK method to provide a more systematic and reliable evaluation of occupational risks. Gul et al. (2018) introduced a comprehensive risk assessment framework that integrates the Fine-Kinney method with fuzzy AHP and fuzzy VIKOR to address uncertainty and improve decision-making in industrial safety management. Dagsuyu et al. (2020) presented an enhanced Fine-Kinney risk assessment method that incorporates a clustering approach to improve the prioritization of risks. Gul and Celik (2018) proposed a new approach by combining the FK and rule-based fuzzy system approach and demonstrated the importance of the model by applying the railway industry. The other hybrid approach that combines the ANFIS and FK approaches was proposed by Gökler et al. (2022). As can be seen, the use of the FK method in conjunction with fuzzy-based methods is quite common.

The other important method used in risk assessment is the matrix method. Bayraktar et al. (2019) used the L matrix method to analyse the non-structural risks of schools. Öztürk and Şimşek (2020) used the matrix risk assessment method in the risk assessment for roof works and provided recommendations for the measures to be taken against risks. Soykan (2018) carried out a risk assessment with L-type matrix method in industrial fishing vessels. Kabakulak (2019) used the matrix method for a textile company.

In the matrix method, only probability and severity parameters are included. The values of these parameters are determined by the occupational health and safety expert. However, it is not possible to determine the probability of an event occurring with a single point value. Also, the probability of an event occurring is related to its frequency. Therefore, as in the matrix method, it is possible to perform risk scoring using only probability and severity components. As in the FK method, the matrix method is limited in terms of flexibility as it uses a single estimation value for probability and severity values. In this study, a generalized version of the matrix method, the Cartesian product method, is introduced. The Cartesian product method is a method based on probability and severity parameters as in the matrix method. This method

is designed to be more flexible and inclusive than the existing matrix method. The Cartesian product method provides flexiblity in determining the probability and severity parameters. In the Cartesian product method, the expert can determine the probability and severity parameters for the identified risk within a range rather than a fixed value. The Cartesian product method aims to eliminate the limitations of the matrix method. In addition, a web application is developed using the shiny package in R software to ensure the applicability of the Cartesian product method by the experts.

The other sections of the study are designed as follows. Section 2 includes risk scoring methods. In Section 3, risk scoring methods are compared on a real application. In Section 4, the developed tool for the proposed model, called as CPMRisk, is introduced. The results of the study are summarized in Section 5.

2. RISK SCORING METHODS

In this section, three different methods are summarized for risk scoring. These are matrix, FK and Cartesian product methods. Before moving on to risk scoring methods, the basic concepts that should be known are given. These are frequency, severity and probability.

Frequency: Repetition or duration of exposure to the hazard over time. It will be expressed numerically with probability in the criterion.

Severity: It is the estimated harm that the realization of the hazard will cause on human and workplace.

Probability: It is the expression of the occurrence of an event that has the potential to harm the employee, third party and / or workplace, taking into account the frequency.

After the hazards are identified, for each hazard, an assessment is made regarding the probability of the event that may occur due to this hazard. Probability refers to how often contact with the hazard is likely to occur or how long exposure occurs, and the following points are taken into account when making judgements about the probability of the event related to the hazard.

- Number of people exposed to the hazardous situation,
- The number of occurrences of the hazard in a given time interval (frequency),
- Duration of exposure to hazard,
- Environmental conditions,
- Residual risk,
- The proficiencies of the people involved in the situation in question,
- Attention/distractions,
- Human error, overtime and leave situations,
- Maintenance and repair weaknesses,
- Complexity of instructions,
- Difficulties in working in accordance with the determined flow,
- Failure to put control measures in place.

Furthermore, when calculating the probability of the risk associated with the hazard source, a list of unsafe behaviors needs to be established. Thus, the occupational health and safety

expert can reliably estimate the probability. The ratio of observed unsafe behaviors to total unsafe behaviors gives an estimate for the probability of the related risk. In the remaining part of this section, risk scoring methods are given.

2.1. Matrix Method

The risk value in matrix method is calculated by

$$R = P \times S \tag{1}$$

where P is the probability and S is the severity. Tables 1 and 2 show the probability and severity values according to the matrix method. Both parameters take discrete values in the range of 1-5.

Table 1. Probability Values and Corresponding Descriptions (Aker and Özçelik, 2020)

Probability	**Description**
Very low (1)	Occurs hardly ever
Low (2)	Occurs Once a year
Moderate (3)	Occurs a few times a year
High (4)	Occurs once a month
Very High (5)	Occurs very often

Table 2. Severity Values and Corresponding Descriptions (Aker and Özçelik, 2020)

Severity	**Description**
Very low (1)	Requires only first aid
Low (2)	Requires outpatient treatment and first aid
Medium (3)	Requires inpatient treatment
High (4)	Requires long-term treatment
Very high (5)	Death or permanent incapacity

Probability	Severity				
	Very low	Low	Moderate	High	Very High
Very low	1	2	3	4	5
Low	2	4	6	8	10
Moderate	3	6	9	12	15
High	4	8	12	16	20
Very High	5	10	15	20	25

Figure 1. Risk scoring in matrix method (Çeliktaş and Ünlü, 2018).

Figure 1 shows how to classify the risk values obtained by the matrix method. Here, a value of 25 represents unacceptable risk. The meanings of the values given in Figure 1 are as follows: 20-25 is unacceptable risk, 15-16 is significant risk, 8, 9, 10, 12 is moderate risk, 2, 3, 4, 5, 6 is acceptable risk and 1 is insignificant risk (Çeliktaş and Ünlü, 2018).

2.2. FK Method

The FK method, introduced by Kinney and Wiruth (1976), is generally used by small-scale companies. The following equation is used to calculate the risk in FK method

$$R = P \times S \times F \qquad (2)$$

where F is the frequency. In FK method, the risk value is obtained from the multiplication of these three parameters (Ilbahar et al., 2018). The values of these parameters and their definitions can be found in Kinney and Wiruth (1976). The risk score obtained by FK method is divided into 5 classes as acceptable risk, possible risk, substantial risk, high risk and very high risk (see, Figure 2).

Risk	Description
>400	Very high risk; consider
200 to 400	High risk; immediate correction
70 to 200	Substantial risk; correction
20 to 70	Possible risk; attention
<20	Risk; perhaps acceptable

Figure 2. Risk classification intervals for FK method (Kinney and Wiruth, 1976)

2.3. Cartesian Product Method

The Cartesian product method is a risk scoring method based on two parameters. These are probability and severity parameters. The probability and severity parameter ranges used in the matrix and the FK methods are difficult to interpret mathematically. Probability values should be defined in the range [0,1]. Defining inappropriate ranges for probability values leads to inaccurate expression of the relationship between probability and severity parameters. The relationship between probability and severity is $\text{Severity} \leq \text{Severity} \times \text{Probability}$ and this relationship is not provided in matrix and FK methods. The product of $\text{Severity} \times \text{Probability}$ is an upper bounded function with the severity parameter.

In both Matrix and FK method, probability and severity values are expressed with a single value. However, when determining the risk of an identified hazard, many possibilities are evaluated together. For example, the risks related to the hazard source can be expressed as a simple hand cut, loss of limb and death. In this case, the severity value for this risk should be expressed as a range covering all three risk values. Likewise, the probability value cannot be expressed by a single value. The probability of the risk depends on many parameters. For example, the risk of amputation or loss of limb of a worker may vary according to the experience, environmental conditions and working hours of the individuals operating the relevant machine. Depending on these parameters, the probability of the risk should be expressed as a range.

When making a judgement about the probability of the risk rising from the hazard in question, the intervals in Table 3 are used. When determining the probability intervals in the Table 3, it is taken into consideration that the probability of an event is only be a real number in the range (0,1].

Table 3. Probability Values of the Cartesian Product Method

Probability	Description	Probability Interval
Very low	Unlikely (once every 5 years)	(0-0.2]
Low	Likely (1 or 2 days per year)	(0.2-0.4]
Moderate	Possibly	(0.4-0.6]

High	(1 day every 6 months or 6 days a year) Very likely (2 days a month or 10-12 days a year)	(0.6-0.8]
Very high	Always near and within the reach of hazard	(0.8-1]

In order to ensure an accurate approach in determining the estimate of the severity of the hazard without control measures, it is essential to select any of the desired subintervals from the interval [0,100]. Table 4 is used to select these intervals.

Table 4. Severity Intervals

Severity	**Description**	**Value**
None	no incident	0
Very mild	No work hours lost (situations where first aid is adequate)	(0-20]
Mild	No working day loss (first aid and medical treatment required)	(20-40]
Moderate	Accident with loss of working day (treatment required)	(40-60]
Serious	Death, loss of limb, severe ınjury, occupational disease (long treatment)	(60-80]
Very serious	Multiple deaths	(80-100]

In the risk scoring process, the numbers which are the products of the arithmetic averages of the interval bound values selected separately for probability and severity are used as numerical symbols of the determined intersection clusters, i.e. risk areas. The intervals in Figure 3 are used to determine the degree of the risk. Note that if the severity score is between 60 and 80, the risk value is considered ‘high risk’ regardless of the probability value, and between 80 and 100 is considered as ‘very high risk’.

Risk	Description
R=0	No risk
0<R≤10 (Very low)	No need to take control measures
10<R≤30 (Low)	Personal protective equipment must be used
30<R≤60 (Moderate)	Administrative control
60<R≤80 (High)	Engineering control
80<R≤100 (Very high)	The work is completely stopped

Figure 3. Risk classification based on the Cartesian product method.

3. APPLICATION

In a tire manufacturing company, a risk assessment related to the bambury machine is performed and 7 hazard sources and risks related to these hazard sources are identified. Hazards and risks are given in Figure 4 and risk scoring is carried out according to 3 different methods. Based on the evaluation of risk scoring methods, it is observed that the matrix method has 4 moderate risks, 2 low risks, and 1 high risk. The FK method consists of 3

moderate risks, 2 low risks, 1 high risk, and 1 very low risk. Furthermore, the Cartesian product method includes 2 very high risks, 1 high risk, 2 moderate risks, 1 low risk, and 1 very low risk.

In the 1st and 2nd risk assessment, since the severity values are determined in the range of 80-85, these risk values are evaluated in the very high risk category according to the Cartesian product method. The agreement between these 3 methods is analyzed. The degree of agreement is calculated as the ratio of matching risk categories to the total category. Accordingly, the agreement between the matrix and Cartesian product method is 57.14% (4/7), and the agreement between FK and Cartesian product method is 71.43% (5/7).

Cartesian product and the FK methods produce different results for 2 cases. Matrix method and Cartesian product method give different results for 3 cases. The reason for this is that the Cartesian product method performs risk classification regardless of the probability parameter when the severity value is above the determined threshold level.

Matrix method and Cartesian product method give different results for 3 cases. In 2 of them, the severity value is above the determined threshold value. In the 7th risk assessment, while the matrix method gives a low risk classification, both FK and Cartesian product methods give a very low risk classification.

Order	Source of Hazard	Hazard	Risk	Matrix			FK				Cartesian				
				P	S	R	P	F	S	R	P		S		R
											a	b	a	b	
1	BAMBURY 5 UNIT	LAPPING PROCESS/ELECTRICITY	BURN, INJURY, DEATH AS A RESULT OF ELECTRIC SHOCK IN CASE OF ELECTRIC LEAKAGE WHILE WORKING IN THE MOULDING SECTION OF THE BAMBURY UNIT AND CONTACT OF THE EMPLOYEE	2	4	8	1	2	15	30	0.20	0.30	80	85	20.6
2	BAMBURY 5 UNIT	LAPPING PROCESS/ELECTRICITY	FAILURE TO TAKE ADEQUATE MEASURES RELATED TO ELECTRICAL PANELS (OPEN LIDS, CONTACT BY UNAUTHORISED AND UNINFORMED PERSONS, NOT USING INSULATED MATS, PRESENCE OF CONDUCTIVE LIQUIDS IN THE PANEL AREA, DIVERSION IN THE INSTALLATION, ETC.). IN CASE OF BURN, INJURY, DEATH DUE TO ELECTRIC SHOCK	3	4	12	3	3	15	135	0.40	0.50	80	85	37.1
3	BAMBURY 5 UNIT-SPINDLES	PRESENCE IN THE WORKPLACE / TEMPERATURE OF THE CYLINDER AND PRODUCT	IN CASE OF CONTACT WITH THE CYLINDER OR THE PRODUCT WITH A TEMPERATURE OF AROUND 150 DEGREES DURING THE PROCESS IN THE MOULDING AREA FOR REASONS SUCH AS MAKING ADJUSTMENTS IN THE AUTOMATIC WORKING MACHINE, MAKING THE FIRST OPERATIONS, INJURY AS A RESULT OF BURNING WITHOUT USING GLOVES	4	3	12	6	3	7	126	0.80	0.90	35	45	34.0
4	BAMBURY 5 UNIT-SPINDLES	PRESENCE AT WORK / SMOKE - ODOUR - VAPOUR FROM DOUGH	OCCUPATIONAL DISEASES THAT MAY OCCUR AS A RESULT OF CHEMICAL EXPOSURE FROM FUMES AND ODOURS EMITTED WHILE IN THE ENVIRONMENT FOR ANY REASON	5	2	10	10	6	3	180	0.80	0.90	35	45	34.0
5	BAMBURY 5 UNIT-SPINDLES	DOUGH CUTTING PROCESS / SPINDLE MOVEMENT	INJURY, SERIOUS INJURY, DEATH IN CASE OF CARELESS BEHAVIOUR OF THE EMPLOYEE WHILE WORKING BY HEATING THE METAL SHOVEL BY USING THE FLAME OF OXYGEN WELDING FLAME TO BREAK AND REMOVE THE DOUGH WHEN THE DOUGH IS STUCK AND COLLECTED UNDER THE SHAFT	3	5	15	6	1	40	240	0.40	0.50	50	65	25.9
6	BAMBURY 5 UNIT-TANK STAIRS	PRODUCT DELIVERY TO THE POOL TANK / HEIGHT OF TANK LADDERS	INJURY IF THE EMPLOYEE FALLS DUE TO ACCIDENT AND CARELESSNESS OR CORROSION (CORROSION) OF THE LADDER STEPS OVER TIME WHILE CLIMBING TO THE PLATFORM BUILT TO PUT PRODUCTS IN THE POOL TANK	2	2	4	1	3	7	21	0.20	0.30	40	45	10.6
7	BAMBURY 5 UNIT-POOL TANK	PRODUCT DELIVERY PROCESS TO THE POOL TANK / MOVEMENT OF TANK EQUIPMENTS	INJURY IF THE EMPLOYEES AND ESPECIALLY THE EMPLOYEE WHO PUTS PRODUCT INTO THE TANK PUTS HIS HAND INTO THE TANK WHILE THE TANK APARTS ARE MOVING FOR UNFORESEEN REASONS AND TOUCHES THE MOVING EQUIPMENT.	1	3	3	1	2	3	6	0.10	0.20	50	60	8.3

Figure 4. Comparison of the methods.

4. CPMRISK

CPMRisk is designed in R software using the shiny package and can be accessed from https://nusretefendioglu.shinyapps.io/CPMRisk/.

CPMRisk is very easy to use. The user enters the lower and upper bound values for probability and severity parameters, the system automatically calculates the risk level and determines its position on the heat map. In addition, the system provides information about the measures to be taken according to the determined risk class (see, Figure 5).

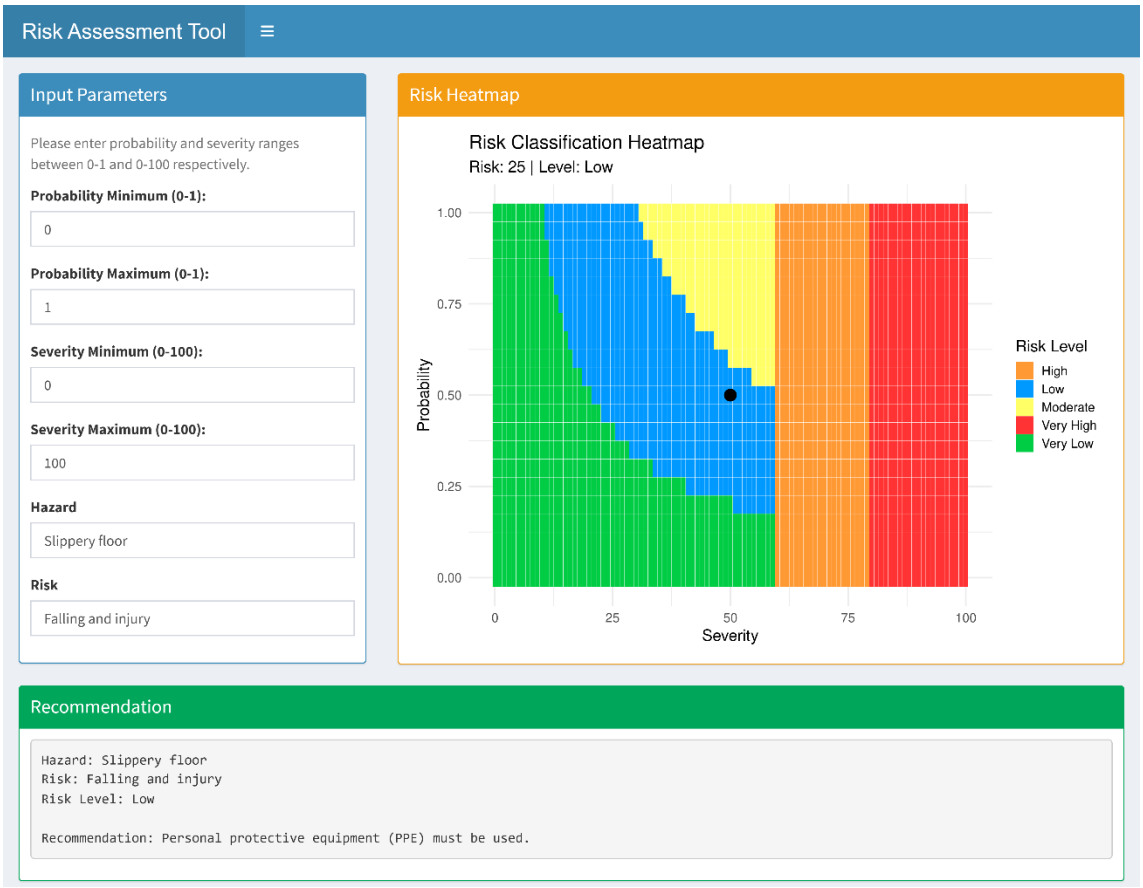

Figure 5. CPMRisk web-tool.

5. CONCLUSION AND FUTURE WORK

In this study, Cartesian product method is proposed. The Cartesian product method is a system based on the fact that probability and severity parameters cannot be expressed as a single value. With this method, all factors affecting the probability and severity parameter values are taken into consideration and lower and upper bound values are determined for these values. The effectiveness of the method is compared with matrix and FK method. In the application study carried out in a tire manufacturing company, it was observed that FK and Cartesian product methods gave similar results. The Cartesian product method provides the occupational health and safety expert with flexible thinking and application in the risk scoring process. In addition, a web application named CPMRisk was developed. Thanks to this application, the user can easily obtain the risk scoring for the probability and severity value determined by the user.

In the future work of the presented study, an artificial intelligence based recommendation system will be established. Depending on the identified hazard source and risk, it will inform the occupational health and safety expert about the measures to be taken according to the calculated risk score.

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ETYMOLOGY OF PHANACIDINI TAXA (CYNIPOIDEA: CYNIPIDAE)

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Abstract: The etymology of taxon names (genera and species) within the tribe Phanacidini (Cynipidae), which predominantly occurs in the Palearctic region and primarily induces galls on plants of the family Asteraceae, is examined here in detail for the first time. It is clearly demonstrated that the naming of species in this group largely relies on their host plants. Additionally, both genus- and species-level names are influenced not only by dedications to individuals but also by morphological characteristics and geographic names. Given the diversity of Phanacidini species, etymological analyses of their scientific names provide a valuable reference resource. The compilation of these data is of great importance for understanding the role of accurate and meaningful nomenclature in scientific communication and the documentation of biodiversity.

Keywords: Cynipid, Binomial nomenclature, Etymology, Asteraceae.

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1. INTRODUCTION

The binomial nomenclature system, which underpins modern biological classification, was formalized by Carl Linnaeus in Species Plantarum (1753) and later extended to animals in the 10th edition of Systema Naturae (1758) (Lodos, 1979; Winston, 1999, 2018; Knapp et al., 2004). This structure facilitated scientific communication and enabled the consistent classification of biodiversity across regions and disciplines. When *Systema Naturae* was published, Latin was the common language of science, so Linnaeus and his contemporaries saw no need to explain name origins. As classical languages declined, the meaning of some taxon names became unclear. Over time, as the use of classical languages declined, understanding the origins of some taxon names became more challenging, leading to an increased focus on documenting their etymology. Following the establishment of the International Commission on Zoological Nomenclature (ICZN) and its codes, the origins of taxon names have been increasingly well documented over the past fifty years (Ride et al., 1999; Karataş and Karataş,

2023). The etymology of newly described taxa explains the origin, rationale, and formation of the name (Winston, 1999).

Scientific names assigned to newly described taxa by researchers can be categorized into various groups, such as morphonyms, eponyms, autochthonyms, toponyms, bionyms, taxonyms, ergonyms, anagrams, and tautonyms (Karataş and Karataş, 2023). Morphonyms are based on morphological traits; eponyms honor real or mythological figures; autochthonyms are derived from local languages. Toponyms refer to geographic locations; bionyms to natural habitats; taxonyms to previously established taxa. Ergonyms reflect behavioral traits; anagrams are formed by rearranging letters; and tautonyms occur when genus and species names are identical (Karataş and Karataş, 2023). While these names arise from diverse origins, the rules governing their formation are codified by the *Code*.

The *Code* clearly defines the rules for the formation and modification of species-group names. At the genus and species levels, all names must be in Latin or appropriately latinized. For names honoring individuals, the suffix "-i" is used for man and "-ae" for woman. If the species epithet is an adjective or participle, it must agree in gender with the generic name. However, eponyms are generally treated as nouns and are formed using only the appropriate gendered suffix (Ride et al., 1999; Dubois, 2007; Braby et al., 2024).

The tribe Phanacidini (Cynipoidea: Cynipidae) predominantly comprises species that induce galls on plants belonging to the family Asteraceae, with most galls forming specifically on the stems. It includes four genera: *Asiocynips* Kovalev, 1982, *Diakontschukia* Melika, 2006, *Phanacis* Förster, 1860, and *Zerovia* Diakontshuk, 1988. While the tribe is native to the Palearctic region, it has been introduced to various other parts of the world and currently encompasses a total of 41 recognized species (Nastasi et al., 2025).

This study aims to examine the origins and structural features of Latin taxon names of cynipid species belonging to the tribe Phanacidini, which are distributed worldwide. The compiled etymological data contribute to a better understanding of scientific naming standards in the processes of species identification, classification, and nomenclature, while also serving as a valuable reference source for both researchers and enthusiasts.

2. MATERIALS AND METHODS

The currently valid species belonging to the tribe Phanacidini (Cynipidae), which are predominantly distributed in the Palearctic region and typically induce galls on plants in the family Asteraceae, have been listed in alphabetical order by Nastasi et al. (2025). In addition to the list, the original sources in which these taxa were first described are also discussed in detail. Following each taxon name, the author and the year of description are provided. For newly described taxa, if the original sources include etymological information, these statements have been quoted verbatim within quotation marks (""). In cases where no explicit etymology is provided, the relevant literature—particularly the taxon descriptions and accompanying notes—has been carefully examined, and potential clues regarding the origin of the name have been thoroughly evaluated in an effort to infer its etymology. When no etymological information was provided in the original descriptions, online resources containing Latin and Ancient Greek dictionaries (e.g., Latinitium, Logeion, The Perseus Digital Library) were used to explore the meanings of taxon names. Definitions from these sources were cross-referenced to verify their accuracy, and the original root forms identified in the dictionaries were included

in the study. Alongside the proposed meanings, Latin inflectional endings and Ancient Greek spellings were also documented.

Abbreviations: adj.: adjective; class.: classic; cf.: confer (compare); f. or fem.: feminine; gen.: genitive; Gr.: Greek; Lat.: Latin (classic); late Lat.: late Latin; m.: masculine; n. or neut.: neuter; pl., plu. or plur.: plural; subst.: substantive, -ly; syn.: synonym, -ymous; v.: verb, vide.

3. RESULTS

When examining the distribution of taxon names based on their etymological origins, the most frequently used naming category at the species level is bionym, with 22 examples. Species names derived from eponyms, morphonyms, and toponyms were used seven, seven, and five times, respectively. In contrast, genus-level names show less diversity: eponyms were used twice, while morphonyms and toponyms were each used only once. Notably, bionym names were not used at the genus level (Figure 1).

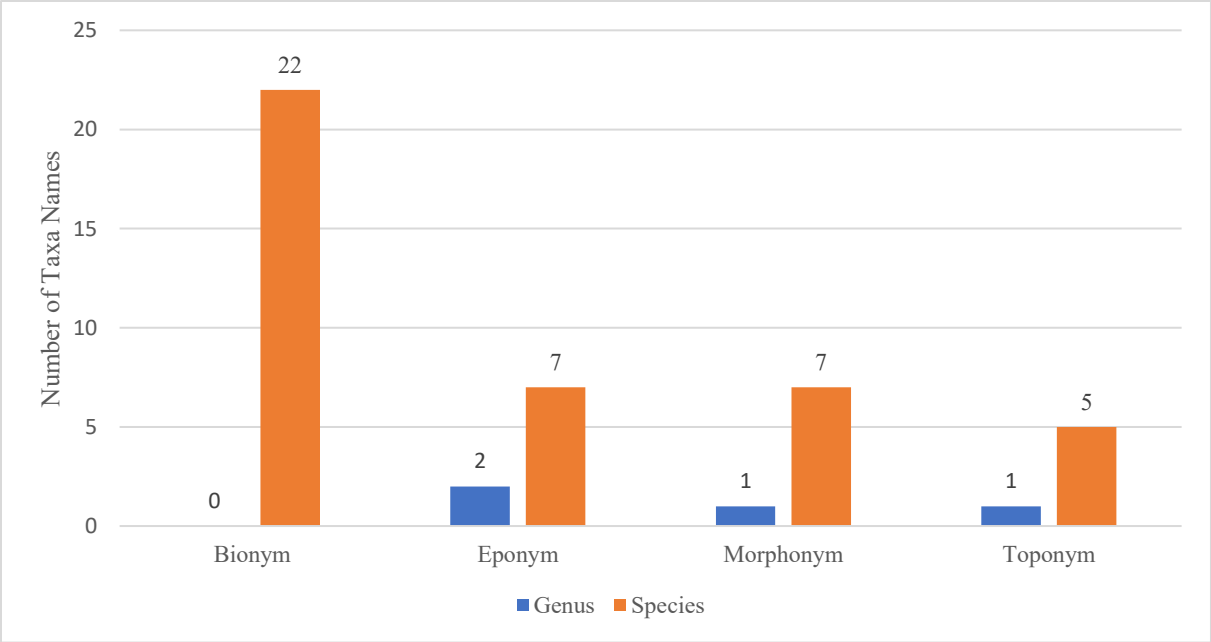

Figure 1: Etymological Categories of Phanacidini Taxa Names

3.1. The Etymology of Scientific Names

Tribe PHANACIDINI Nieves-Aldrey, Nylander & Ronquist, 2015 (41 species) (Derived from type genus *Phanacis* Förster, 1860)
phanacidini = Derived from φανός, ή, όν (visible, distinct) and ἀχις (the point); refers to the ovipositor sheath projecting as a distinct point. In the original text (German): "*Von φανός, ή, όν, sichtbar, deutlich und ἀχις die Spitze, bezieht sich auf die als deutliche Spitze hervorragende Legescheide*." (Förster, 1860). + -**ini** *pl*. Lat.: The suffix is used for a tribe name in zoological nomenclature (Ride et al., 1999).

Genus *Asiocynips* Kovalev, 1982 (4 species) (toponym)

asiocynips = In collections from Central Asia and Kazakhstan, several species of the new genus have been discovered. In the original text (Russian): "В сборах из Средней Азии и Казахстана обнаружено несколько видов нового рода, ..." (Kovalev, 1982).

***Asiocynips caulina* Diakontshuk, 1988** (bionym)

caulis (**cōlis**; and **coles**; cf. cauliculus), is, *m*., = καυλός, *the stalk or stem of a plant* (Lewis and Short, 1879). **caulias**, ae, *m*., = καυλίας, *taken* or *derived from the stalk* (Lewis and Short, 1879).

***Asiocynips cousiniae* Diakontshuk, 1988** (bionym)

cousiniae = Named from its host plant, *Cousinia* Cass. (Diakontshuk, 1988). The plant genus name is likely given in honor of the psychologist Victor Cousin. In the original description (French): "*...que nous dédions au célèbre psychologiste Victor Cousin*. (*…which we dedicate to the famous psychologist Victor Cousin*.)" (Cuvier, 1827).

***Asiocynips lugubris* Kovalev, 1982** (morphonym)

lūgŭbris (lūgūbris), e, *adj*. [lugeo and fero], *of* or *belonging to mourning, mourning*- (Lewis and Short, 1879). In Latin, *lugubris* also means *sorrowful, gloomy, dark*, or *dull*. In zoology, this adjective is typically used in cases where: (1) the species has dark, dull, or somber coloration patterns, (2) or the general appearance of the species gives a "*melancholy*" or "*unadorned*" impression. It is understood that the author may have given this name due to the body coloration and overall appearance of the species.

***Asiocynips pannucea* Kovalev, 1982** (morphonym)

pannūcĕus and **pannūcĭus**, a, um, *adj*. [pannus], *ragged, tattered*. **I. Lit.:** *Subst*.: **pannūcĕa**, ōrum, *n*., *rags*. **II. Transf.,** *wrinkled, shrivelled, flabby* (Lewis and Short, 1879). It is understood that the author may have given this name due to a morphological characteristic.

Genus *Diakontschukia* Melika, 2006 (1 species) (eponym)

diakontschukia = "This species is named in honour of L.A. Diakontshuk (=Diakontschuk)" (Melika, 2006). **-ia** *f*. (*m*. -ius, *n*. -ium) Lat.: The Latin suffix is used for a genus name in zoological nomenclature, if the personal name ends in a consonant (Ride et al., 1985).

***Diakontschukia saussureae* (Diakontshuk, 2001)** (bionym)

saussureae = Named from its host plant, *Saussurea* DC. (Diakontshuk, 2001). This plant genus name is dedicated to the Swiss naturalists Horace-Bénédict de Saussure (1740-1799) and his son Nicolas-Théodore de Saussure (1767-1845).

Genus *Phanacis* Förster, 1860 (35 species) (morphonym)

phanacis = Derived from φανός, ή, όν (visible, distinct) and ἀχις (the point); refers to the ovipositor sheath projecting as a distinct point. In the original text (German): "*Von φανός, ή, όν, sichtbar, deutlich und ἀχις die Spitze, bezieht sich auf die als deutliche Spitze hervorragende Legescheide*." (Förster, 1860).

***Phanacis carthami* Gussakovkij, 1933** (bionym)

carthami = Named from its host plant, *Carthamus* L. (Rodd et al., 1933). The plant genus name derives from Arabic *qurṭum*, which comes from Classical Syriac *qūrṭəmā* (safflower), ultimately rooted in *qarṭem*, meaning "*to cut off gently*", referring to the harvesting of petals for dyeing. **-i** *gen*. Lat.: The suffix.

***Phanacis caulicola* (Hedicke, 1939)** (bionym)

caulĭcŭlus or **cōlĭcŭlus**, i, *m*. dim. [caulis], *the small stalk* or *stem of a plant* (Lewis and Short, 1879). **-cola** *m*., (*gen*., **-colae**) Lat.: This suffix means "*dweller*" or "*inhabitant*". It refers to an

organism that lives on or is associated with the host plant. In original gall description: "*The gall (of which there is no indication from the outside) consists of an ellipsoidal cell in the pith of the stem of Picris echioides L*. (Synonym of *Helminthotheca echioides* (L) Holub)." (Hedicke, 1939). It is understood that the author chose this name because the larval chambers are located in the stem of the host plant.

***Phanacis centaureae* Förster, 1860** (bionym)

centaureae = Named from its host plant, *Centaurea* L. (Förster, 1860). **centaurēum** or **-ĭon**, i, *n*. (access. form *centaurĭa*, ae, *f*.): κενταύρειον and κενταύριον, *centaury*. **Chīron** (*nom*. **Chīro**), ōnis, *m*., = Χείρων, *one of the Centaurs*, distinguished for his knowledge of plants, medicine, and divination, *son of Saturn and Philyra*. **Centaurus**, i, m., = Κένταυρος, *a Centaur*; *the Centaurs were wild people in the mountains of Thessaly, who fought on horseback*; acc. to the fable, monsters in Thessaly of a double form (the upper parts human, the lower those of a horse) (Lewis and Short, 1879). **-ae** *gen*., Lat.: The suffix.

***Phanacis chondrillae* (Gain, 1894)** (bionym)

chondrillae = Named from its host plant, *Chondrilla juncea* L. (Asteraceae). **chondrillē (chondryllē),** ēs, *f*., or **chondrillon**, i, *n*., = χονδρίλλη, *chondrilla*, *Spanish succory* (Lewis and Short, 1879). **-ae** *gen*., Lat.: The suffix.

***Phanacis ciceki* Azmaz & Katılmış, 2021** (eponym)

ciceki = "In honour of Assoc. Prof. Dr Mehmet Çiçek who is an expert botanist" (Azmaz and Katılmış, 2021). **-i** *gen*. Lat.: The suffix.

***Phanacis cichorii* (Kieffer, 1909)** (bionym)

cichorii = Named from its host plant, *Cichorium intybus* L. (Kieffer, 1909). **cĭchŏrĭum** or **-on** (**cĭchŏrēum**), ii, *n*., = κιχόρια (usually κιχώριον), *chiccory, succory*, or *endive* (Lewis and Short, 1879). **-i** *gen*. Lat.: The suffix.

***Phanacis comosae* Nieves-Aldrey, 2008** (bionym)

comosae = "Named after the host plant, *Picris comosa* (Boiss.) Benth. & Hook. f. ex B. D. Jacks. (Synonym of *Helminthotheca comosa* (Boiss.) Holub)" (Nieves-Aldrey et al., 2008). **cŏmōsus**, a, um, *adj*. [coma], *hairy, with much* or *long hair* (rare) (Lewis and Short, 1879).

***Phanacis cousiniae* Diakontshuk, 1988** (bionym)

cousiniae = Named from its host plant, *Cousinia* Cass. (Diakontshuk, 1988). The plant genus name is likely given in honor of the psychologist Victor Cousin. In the original description (French): "*...que nous dédions au célèbre psychologiste Victor Cousin*. (*…which we dedicate to the famous psychologist Victor Cousin*.)" (Cuvier, 1827).

***Phanacis crassinervis* Diakontshuk, 1980** (morphonym)

crassinervis = **crassus**, a, um, *adj*. [Sanscr. kart-, to spin; cf.: crates, cartilago, etc.]; as opp. to flowing, thin, lean, delicate, etc., *solid, thick, dense, fat, gross*, etc. (Lewis and Short, 1879) + **nervus**, i, *m*. [root snar-; Old Germ. snara, a snare; Gr. νεῦρον; cf. parvus and παῦρος], *a sinew, tendon, nerve* (Lewis and Short, 1879). In the original description (Russian): "Жилки явственные, коричневые. Радиальная жилка R1 и R2 более темная, чем субкостальная Sc. (*The veins are distinct and brown. The radial veins R1 and R2 are darker than the subcostal vein Sc.*)" (Diakontshuk, 1980). It is understood that the author may have given this name due to the wing venation, which is a distinguishing feature of the species.

***Phanacis dobrogicus* Şchiopu, Tataroğlu & Katılmış, 2024** (toponym)

dobrogicus = "Derived from the name of Dobrogea Province (Southeastern Romania) where this species was first time found. Noun in apposition" (Şchiopu et al., 2024). **-icus** *m*. (*f*. **-ica**, *n*. **-icum**) Lat.: The suffix indicates *belonging to, derived from*, or *pertaining to something*, *often suggesting a connection*. It is used to form *some substantivized nouns from other nouns*, helping to express characteristics or relationships to a particular source or concept.

***Phanacis eryngi* (Diakontshuk, 1984)** (bionym)

eryngi = Named from its host plant, *Eryngium* L. (Diakontshuk, 1984). **ērynge**, ēs, *f*., and **ēryngĭon**, ii, *n*., = ἠρύγγη and ἠρύγγιον, *a sort of thistle* (Lewis and Short, 1879). **-i** *gen*. Lat.: The suffix.

***Phanacis eugeniae* (Diakontshuk, 1981)** (eponym)

eugeniae = **eugĕnēus** or **-īus**, a, um, *adj*., = εὐγενής, *well-born*, i. e. *noble, generous* (Lewis and Short, 1879). **-ae** *gen*. Lat.: This suffix indicates "*possession*" or "*association*" and is added to the end of woman names (Ride et al., 1999). It is understood that the author dedicated this name to a woman (Eugenia or Eugenie).

***Phanacis helminthiae* (De Stefani, 1902)** (bionym)

helminthiae = Named from its host plant, *Helminthia aculeata* DC. (Synonym of *Helminthotheca aculeata* (Vahl) Lack) (De Stefani, 1902). The plant genus name comes from Ancient Greek ἕλμινθος (hélminthos), genitive singular of ἕλμινς (hélmins, "worm").

***Phanacis heraclei* (Hedicke, 1923)** (bionym)

heraclei = Named from its host plant, *Heracleum sphondylium* L. (Hedicke, 1923). **Hēraclēus** or **-clĭus**, a, um, *adj*., *of* or *belonging to Heraclea* (in Lydia), *Heraclean* (Lewis and Short, 1879). **-i** *gen*. Lat.: The suffix.

***Phanacis heteropappi* Diakontshuk, 1988** (bionym)

heteropappi = Named from its host plant, *Heteropappus canescens* L. (Diakontshuk, 1988). **hetero**: A Greek-derived prefix meaning "*different*" or "*varied*" + **pappus**, i, *m*., = πάππος. **I.** *An old man*. **II.** *The woolly, hairy seed of certain plants*. **III.** *A plant, also called* erigeron (Lewis and Short, 1879). **-i** *gen*. Lat.: The suffix.

***Phanacis hypochoeridis* (Kieffer, 1887)** (bionym)

hypochoeridis = Named from its host plant, *Hypochaeris radicata* L. (Kieffer, 1887). **hypo**: Greek prefix meaning "*under*" or "*below*" + **chaeris** (Χαίρης): Derived from *chairo* (Χαίρω), meaning "to rejoice" or "to be glad", referring to *joy* or *happiness*. The plant genus name means "*less than joyous*", because of weedy habit.

***Phanacis irani* (Tavakoli & Melika, 2006)** (toponym)

irani = "The species is named after the country, Iran, where it was collected" (Tavakoli and Melika, 2006). **-i** *gen*. Lat.: The suffix.

***Phanacis kiefferi* (Cotte, 1915)** (eponym)

kiefferi = The species was named in honor of M. Kieffer. In original text (French): "*J'ai cru prudent de soumettre mes animaux à M. Kieffer*" (Cotte, 1915). **-i** *gen*. Lat.: The suffix.

***Phanacis lapsanae* (Perris, 1873)** (bionym)

lapsanae = Named from its host plant, *Lapsana communis* L. (Perris, 1873). **lapsăna (lampsăna)**, ae, *f.* (also **lapsănium**, ii, *n.*), = λαψάνη and λαμψάνη, *an edible plant, charlock* (Lewis and Short, 1879). **-ae** *gen*. Lat.: The suffix.

***Phanacis lorestanicus* (Tavakoli & Melika, 2006)** (toponym)

lorestanicus = "The species is named after the Iranian province, Lorestan, where it was collected" (Tavakoli and Melika, 2006). **-icus** *m*. (*f.* **-ica**, *n*. **-icum**) Lat.: The suffix.

***Phanacis lusitanica* (Tavares, 1903)** (toponym)

lusitanica = **Lūsĭtānĭa**, ae, *f*., *the western part of Spain, the mod. Portugal and a part of the Spanish provinces of Estremadura and Toledo* (Lewis and Short, 1879). **-ica** *f.* (*m*. **-icus**, *n*. **-icum**) Lat.: The suffix. The galls were first collected in Lousã (Tavares, 1903), is a town and municipality located in the central region of Portugal, in the district of Coimbra.

***Phanacis maculatus* Diakontshuk, 1988** (morphonym)

măcŭla, ae, *f.* [for malocula, malcula, *dim*.; cf. Sanscr. mala, dirt], *a spot, mark, stain* (class.). (Lewis and Short, 1879). In the original description (Russian): "Голова черная, с желтыми пятнами, … (*The head is black, with yellow spots, …*)" (Diakontshuk, 1988). It is understood that the author may have given this name due to the yellow spots on the head of the species.

***Phanacis neserorum* Melika & Prinsloo, 2007** (eponym)

neserorum = "Named after Stefan and Ottilie Neser, PPRI, Pretoria, for their invaluable contribution to the study of South Africa's fauna of parasitic Hymenoptera. The type material of the new species was collected by Stefan Neser" (Melika and Prinsloo, 2007). **-orum** *gen*. Lat.: The suffix is added to the end of the personal name if the name is of men or of man (men) and woman (women) together (Ride et al., 1985).

***Phanacis phlomidis* Belizin, 1959** (bionym)

phlomidis = Named from its host plant, *Phlomis tuberosa* L. (Synonym of *Phlomoides tuberosa* (L.) Moench) (Belizin, 1959). **phlŏmis**, ĭdis, *f*., = φλομίς, *mullein* (pure Lat. verbascum); cf. phlomos (Lewis and Short, 1879).

***Phanacis phoenixopodos* (Mayr, 1882)** (bionym)

phoenixopodos = Named from its host plant, *Phoenixopus* (*Lactuca*) *vimineus* L. (*Lactuca viminea* (L.) J.Presl & C.Presl) (Mayr, 1882). One often finds the name misspelt "*Phoenixopus*", a spelling that apparently results from a misinterpretation of its etymology. As explained by Cassini (l.c.), *Phaenixopus* means "*with an apparently sticky foot*" and has no relation with *phoenix* (either the mythical bird or the date palm) (Flann et al., 2010).

***Phanacis pillicornis* (Thomson, 1877)** (morphonym)

pillicornis = **pĭlus**, i, *m*., *a hair* (syn.: villus, seta) (Lewis and Short, 1879) + **cornū**, ūs (access. form *cornum*, -i, n.): *a horn*, [kindred with κέρας, and Germ. and Engl. *horn*; cf. also *carina, cervus*] (Lewis and Short, 1879). In the original description (Latin): "…*antennis tenuibus pilosulis,…* (*…with thin, hair-like antennae, …*)" (Thomson, 1877). It is understood that the author gave this name to the species due to this characteristic of the antenna.

***Phanacis rufipes* Ionescu & Roman, 1959** (morphonym)

rufipes = **rūfus**, a, um, *adj*. [kindred with ruber], *red, reddish,* of all shades (Lewis and Short, 1879) + **pēs**, pĕdis, *m*. [kindr. with Sanscr. pād, foot, from root pad, ire; Gr. ποδ-, ποῦς; Goth. fōt; old Germ. vuoz; Engl. foot]: *a foot* of man or beast (Lewis and Short, 1879). It is understood that the author gave this name because the color of the species' legs is described as *rufous* (Ionescu and Roman, 1959).

***Phanacis sonchi* (De Stefani, 1900)** (bionym)

sonchi = Named from its host plant, *Sonchus asper* Willd. (De Stefani, 1900). **sonchus**, i, *m*., = σόγχος, *the herb sow-thistle* (Lewis and Short, 1879). **-i** *gen*. Lat.: The suffix.

***Phanacis strigosa* Melika, Stone & Tavakoli, 2022** (bionym)

strigosa = "Named after the species name of the host plant, *Picris strigosa* M. Bieb. (Asteraceae)" (Tavakoli et al., 2022). **strĭgōsus**, a, um, *adj*. [stringo], *lean, lank, thin, meagre* (Lewis and Short, 1879).

***Phanacis taraxaci* (Ashmead, 1897)** (bionym)

taraxaci = Named from its host plant, *Taraxacum dens-leonis* Desf. (Synonym of *Taraxacum officinale* F.H.Wigg.) (Ashmead, 1897). *Taraxacum* may have been borrowed into Medieval Latin from the Arabic term "*ṭarak̲šaqūn*", which itself came from Persian, meaning "*bitter herb*". **-i** *gen*. Lat.: The suffix.

***Phanacis tavakolii* Melika, Stone & Pujade-Villar, 2022** (eponym)

tavakolii = "In recognition of the continuing contribution of Majid Tavakoli (Lorestan Agricultural and Natural Resources Research Center, Khorramabad, Lorestan, Iran) to studies on gall wasps of Iran" (Tavakoli et al., 2022). **-i** *gen*. Lat.: The suffix.

***Phanacis urhani* Azmaz & Katılmış, 2021** (eponym)

urhani = "In honour of Prof. Dr Raşit Urhan who is a senior acarologist" (Azmaz and Katılmış, 2021). **-i** *gen*. Lat.: The suffix.

***Phanacis urospermi* (Kieffer, 1901)** (bionym)

urospermi = Named from its host plant, *Urospermum picroides* (L.) Scop. ex F.W.Schmidt. (Kieffer, 1901). οὐρά (**ourá**): *tail* (Liddell and Scott 1940) + **sperma**, ătis, *n*., = σπέρμα, *seed, semen, sperm* (Lewis and Short, 1879). The plant genus name means "*tail seed*" or "*seed with a tail*". **-i** *gen*. Lat.: The suffix.

***Phanacis varians* Diakontshuk, 1980** (morphonym)

vărĭo, āvi, ātum, 1, *v.a*. and *n*. [varius]. **I.** Act., *to diversify, variegate, change* (class.). **II.** *Neutr*., *to be diversified, variegated; to change, alter, waver, vary*, etc. (Lewis and Short, 1879). In the original description (Russian): "Вид близок к Ph. Centaureae (Kalt), но отличается наличием параллельных бороздок между парапсидами в верхней части среднеспинки; более коротким и узким брюшком, более округлой грудью. (*The species is close to Ph. centaureae (Kalt), but differs by the presence of parallel grooves between the parapsides in the upper part of the mesoscutum; a shorter and narrower abdomen, and a more rounded thorax*.)" (Diakontshuk, 1980). It is understood that the author may have given this name because the species differs from others due to one or more morphological features.

***Phanacis zwoelferi* Nieves-Aldrey, 1995** (eponym)

zwoelferi = "Named in honour of Dr. Helmut Zwölfer for his prominent work on thistles and their associated insects" (Nieves-Aldrey, 1995). **-i** *gen*. Lat.: The suffix.

Genus *Zerovia* Diakontshuk, 1988 (1 species) (eponym)

zerovia = Named in honour of M.L. Zerova (Diakontshuk, 1988). In the original text (Russian): "Род назваи именем М. Д. Зеровой. (*The genus was named after M. D. Zerova.*)" (Diakontshuk, 1988). **-ia** *f*. (*m*. -ius, *n*. -ium) Lat.: The suffix.

***Zerovia asiaemediae* Diakontshuk, 1988** (toponym)

asiaemediae = Named after Turkmenistan, Repetek, Southeast Karakum (located Central Asia), where it was collected. In the original text (Russian): "Туркмения, Репетек, Юго-Восточные Каракумы, ..." (Diakontshuk, 1988). **Asia** (Ἀσία) refers to the "*continent of Asia*" + **mĕdĭus**, a, um, *adj*. [Sanscr. madhya, the same; Gr. μέσος; Angl.-Sax. midd; Germ. Mitte; cf. dimidius, meridies (medi-), etc.], *that is in the middle* or *midst, mid, middle* (class.) (Lewis and Short, 1879). **-ae** *gen*. Lat.: The suffix. Thus, *asiaemediae* essentially means "*from* or *related to Central Asia*".

4. DISCUSSION

This study explores the naming practices of taxa within the tribe Phanacidini, offering insights into the etymological roots of their scientific names. The analysis indicates that *bionyms*—names derived from ecological associations such as habitat or host plant (e.g. *A. cousiniae*)—are the most frequently used category, accounting for 48.9% of the cases. Furthermore, a substantial portion of the names consists of *eponyms* (20%), which commemorate individuals (e.g. *P. urhani*); *morphonyms* (17.8%), which reflect morphological features of the insects or the galls they induce (e.g. *P. rufipes*); and *toponyms* (13.3%), which denote the geographical origins of the taxa (e.g. *P. dobrogicus*).

These findings suggest that species-level naming reflects a broader approach, often incorporating biological, morphological, and geographical characteristics of the organisms, whereas genus-level naming tends to be more limited and selective. Moreover, they reflect broader trends in taxonomic nomenclature. In particular, early taxonomic studies either omitted etymological explanations entirely or mentioned them only briefly. However, etymology has now become an almost indispensable part of new species descriptions. This shift has made the naming process more transparent and improved the understanding of the contextual background of taxon names. Moreover, etymological analyses not only clarify the meanings of taxon names but also help us better understand the perspectives and approaches of the scientists who discovered and described these taxa.

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INVESTIGATION OF THE CONDUCTIVITY PROPERTIES OF PYRROLE WITH THE ATTACHMENT OF ELECTRON-DONATING GROUPS (–NH_2) AND (–CL) AS SUBSTITUENTS

ZAFER MAŞLAKCI[1*], AYŞIN ADIN[1]

Abstract: The rapid advancements in science and technology have created the need for the production of new materials with distinct physical and chemical properties, ease of production, and a wide range of applications. Conductive polymers can be used to modify conductivity properties. One method for achieving this modification is by adding different substituents to the monomer. For this purpose, the HOMO-LUMO gap was measured by substituting electron-donating groups (–NH_2 and –Cl) in place of the methyl groups in the phenyl groups of 1-(4-methylphenyl) pyrrole and 3-(4-methylphenyl) pyrrole. The interactions when the substituted phenyl group was attached at the nitrogen position or the carbon position were calculated using the Gaussian16 software package. The configurations obtained were optimized by increasing the chain length from n=1 to n=5. Additionally, the topological properties of the interactions were compared based on electron densities. It was observed that electron-donating groups increased the HOMO energy and decreased the LUMO energy, thereby reducing the band gap and enhancing conductivity. The fact that electron densities are in the opposite direction to conductivity shows that AIM (atom in molecule) theory is a preferable and reliable method for determining conductivity. The incorporation of –Cl and –NH_2 substituents leads to significant changes in the IR spectral properties. Subsequent polymerization results in changes in band intensity and broadening, with small but noticeable frequency and intensity shifts observed between the 1 and 3 isomeric forms.

Keywords: HOMO-LUMO, Pyrrole, Substituent effect, Topological properties.

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1. INTRODUCTION

Polymers are long-chain structures formed by the repeated bonding of small molecules called monomers. This process is known as polymerization. Polymers are widely used due to their ability to be easily modified and their low-cost production methods. Commonly used materials in daily life, such as PVC (polyvinyl chloride) and Teflon (polytetrafluoroethylene), are derived from polymers. Polymers with conjugated structures consisting of alternating single and double bonds are highly effective in providing electrical conductivity. Therefore, such structures are referred to as conductive polymers. Polypyrrole, polythiophene, and polyfuran are widely recognized examples of conductive polymers. With advancements in technology, these polymers are increasingly used in the production of rechargeable batteries, sensors, and electronic devices such as LEDs.

The conductivity mechanism in polymers such as polyacetylene, polyaniline, and polypyrrole, which transmit electricity through electronic means, has not yet been fully understood. For this reason, a theoretical approach called band theory is employed to explain electrical conductivity in conductive polymers (Senevirathne vd., 2011). Conductive polymers are defined as polymers capable of sufficient electrical conductivity through the movement of electrons within their framework. This requires suitable sites within the polymer chain to enable the transport of electrons along the chain. The primary condition for this is the presence of a conjugated system in the polymer's backbone. A conjugated system is described as alternating single and double bonds formed by the overlap of p-orbitals to create π molecular orbitals (Guimard vd., 2007). These π-conjugated polymers are preferred due to their optical and electrical conductivity properties, which make them sufficiently appealing to meet demands (Sahu, 2013).

The conductivity mechanism in polymers such as polyaniline, polypyrrole, and polyacetylene can be explained using band theory. The HOMO-LUMO orbitals and band gap, which serve as the basis for defining electrical conductivity, have been extensively studied experimentally and theoretically and are recognized as a widely accepted theory (Lim vd., 2013; Tuzun vd., 2008; Chaudhry vd., 2013). The electrical properties of polymers can be modified. One of the advantages of conductive polymers is that their properties can be altered by adding different groups to the monomer (Kon vd., 1992). Many studies have been conducted to investigate the effects of substituents attached to polymers on their electrical properties (Sahu, 2013; Chaudhry vd., 2013; Grabowski vd., 2009). Since the discovery of conductive polymers, polypyrrole and polythiophene have been among the most studied polymers in experimental settings (Wang vd., 2001; Sarı vd., 2006). Developing pyrrole derivatives at the nitrogen position has been a preferred approach, as it has been found that such structures exhibit better conductivity values (Sahu, 2013; Kon vd., 1992).

Experimental studies have demonstrated that the polymerization reaction predominantly occurs at the α, α' carbon atom positions. The likelihood of polymerization at the α position is significantly higher compared to the β, β' position (Street vd., 1983). When modifying pyrrole by attaching various substituents, the β position is used to ensure that the position where polymerization occurs remains unoccupied.

Numerous studies have been conducted to contribute to the electronic properties of polymers. According to previous publications, it has been discovered that electron-donating and electron-withdrawing groups can enhance or reduce the conductivity of polypyrrole (Benjamin vd., 2003). Substitution with heteroatoms leads to changes in geometric parameters, as well as electronic, optical, and charge transfer properties (Sahu, 2013; Chaudhry vd., 2013; Grabowski

vd., 2009). Calculations were performed at the B3LYP/6-31+G** level. The agreement between the calculated theoretical values and experimental results serves as evidence that the methods and basis sets used for these materials are reliable (Chaudhry vd., 2013). The DFT method is a highly preferred approach for calculating HOMO-LUMO band energies (Zade vd., 2006; Radhakrishnan vd., 2005; Koepnick 2010; Callegari vd., 2003). An effective approach to polymers with low band gaps and good intrinsic conductivity has been to investigate cases where electron-donating and electron-withdrawing groups interact along the polymer chain (Seo vd., 1999). The geometric structures of polymers are significantly influenced by steric effects, depending on the substituents added to the structure and their positions (Sahu vd., 2013).

The aim of this study is to reveal in detail the effects of $–NH_2$ and –Cl substituents as a strategic approach to increase the electronic conductivity of pyrrole polymers, to analyze the structural-topological changes obtained with different bonding positions and chain lengths, and thus to provide a scientific basis for the design of new generation polymer materials with low band gap and high conductivity.

Based on experimentally examined data, the HOMO-LUMO gap was measured for 1-(4-methylphenyl) pyrrole and 3-(4-methylphenyl) pyrrole, where the substituted methyl groups on the phenyl rings were replaced with electron-donating groups ($–NH_2$ and –Cl). The interactions of the substituted phenyl group, whether attached to the nitrogen position or the carbon atom, were calculated using the Gaussian16 software package. Subsequently, optimizations were performed by increasing the chain length from n=1 to n=5 for the configurations obtained. Additionally, the topological properties of the interactions were determined based on electron densities using the AIMAll software package.

The substituent effect on the pyrrole ring was investigated by using electron-donating groups ($–NH_2$ and –Cl) on the phenyl group and examining their attachment through nitrogen and carbon atoms. The study aimed to explore how the position of the attached group influences conductivity based on the nature of the substituent. Additionally, as the chain length increased, the structural and energetic electronic properties, as well as topological features such as electron density, were analyzed.

2. MATERIAL AND METHOD

In this study, the electronic properties of structures optimized using quantum mechanical calculations were also analyzed through AIM theory. Thus, the study was conducted using two different methods. The Gaussian 16 package program (Frisch vd., 2016) was used for performing quantum mechanical calculations, while the AIMAll package program (Todd vd., 2012) was employed for calculating electronic properties such as electron density. In quantum chemistry software such as Gaussian energy results are usually given in Hartree units. It is used as a standard energy scale in studies such as molecular optimizations, bond energies, and HOMO–LUMO calculations. Firstly, the structures 1-(4-methylphenyl) pyrrole-Cl and 1-(4-methylphenyl) pyrrole-NH_2 were obtained by attaching methylphenyl-Cl and methylphenyl-NH_2 groups to the nitrogen atom of the pyrrole ring, and these structures were subjected to optimization. Subsequently, the structures 3-(4-methylphenyl) pyrrole-Cl and 3-(4-methylphenyl) pyrrole-NH_2 were obtained by attaching methylphenyl-Cl and methylphenyl-NH_2 groups to the carbon atom at the 4-position of the pyrrole ring, and these structures were also subjected to optimization. Finally, optimizations were performed for the configurations obtained from these structures by increasing the chain length from n=1 to n=5.

3. RESULTS

3.1. Monomer Structures

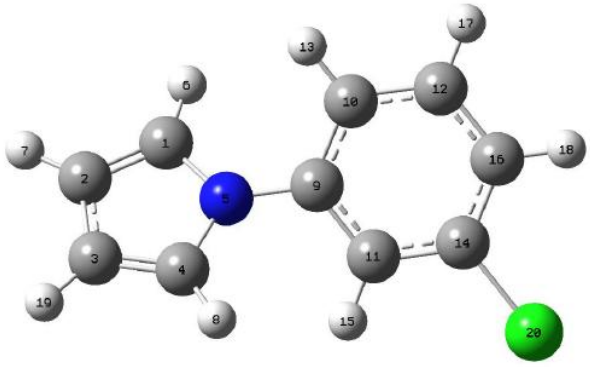
The electronic properties and polymerization reaction of the pyrrole structure were examined through quantum mechanical calculations. The structures 1-(4-methylphenyl)pyrrole-Cl and 1-(4-methylphenyl)pyrrole-NH_2, obtained by attaching methylphenyl-Cl and methylphenyl-NH_2 groups to the nitrogen atom of the pyrrole ring, as well as the structures 3-(4-methylphenyl)pyrrole-Cl and 3-(4-methylphenyl)pyrrole-NH_2, obtained by attaching the same groups to the carbon atom at the 4-position of the pyrrole ring, were subjected to optimization. The resulting structures are presented in Figures 1-5.

The pyrrole monomer has a cyclic structure consisting of five bonds. Its molecular formula is expressed as C_4H_5N. In determining the method and basis set, the experimental HOMO-LUMO bandgap energy value of the pyrrole monomer was measured as 5.84 eV (Chaudhry vd., 2013). The conductivity bandgap energy value calculated as a result of the optimization of the pyrrole monomer at the B3LYP/6-31+G** level is 5.85 eV (Table 1). Within the scope of the study, the method that showed the best compatibility with the experimental data was determined to be DFT (B3LYP) with the 6-31+G** basis set. Following this determination, the data calculated for the pyrrole monomer were compared, and how the 4-methylphenyl group alters the electronic properties of pyrrole was investigated.

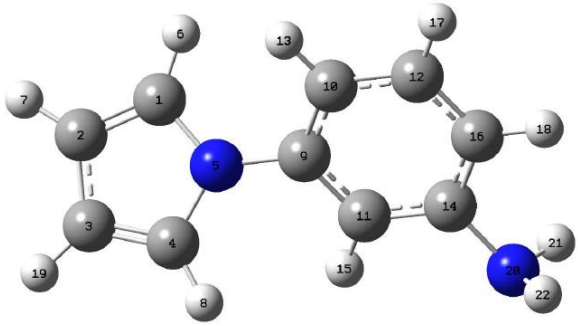
The band gap energy values calculated at the B3LYP/6-31+G** level for the monomer structures 1-(4-methylphenyl)pyrrole-Cl and 1-(4-methylphenyl)pyrrole-NH_2, obtained by attaching methylphenyl-Cl and methylphenyl-NH_2 groups to the nitrogen atom of the pyrrole ring, were found to be 5.03 and 5.17 eV, respectively. Subsequently, the bandgap energy values calculated for the monomers 3-(4-methylphenyl)pyrrole-Cl and 3-(4-methylphenyl)pyrrole-NH_2, obtained by attaching methylphenyl-Cl and methylphenyl-NH_2 groups to the carbon atom at the 4-position of the pyrrole ring, were found to be 5.03 and 5.01 eV, respectively.

Table 1. HOMO-LUMO Energy Values Calculated at the B3LYP/6-31+G** Level for the Pyrrole Monomer.

Pyrrole monomer	**Hartree**			**eV**
	E_{HOMO}	**E_{LUMO}**	**E_{GAP}**	**E_{GAP}**
	-0,216	-0,001	-0,215	5,85



1-(4-methylphenyl) pyrrole-Cl



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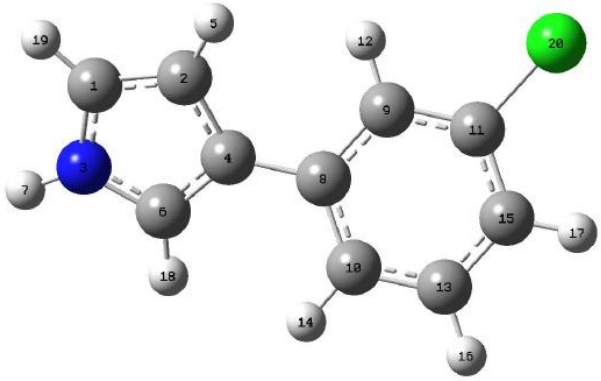
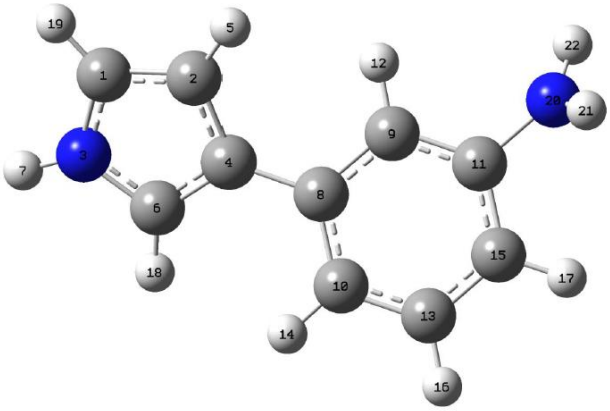


3-(4-methylphenyl) pyrrole-Cl



3-(4-methylphenyl) pyrrole-NH_2

Figure 1. Monomer structures for $(C_4H_5N)_n$ from the Nitrogen Atom and the Carbon Atom

3.2. Substituent Effect

It is possible to modify both the structural and electrical properties of polymers by adding substituents (Kon vd., 1992). It has been observed that the addition of substituent groups to nitrogen and carbon atoms in polymers results in different structural and electrical properties in both cases (Sahu vd., 2013). For this reason, the substitution process has been carried out on nitrogen and carbon atoms.

In its pure form, pyrrole has a HOMO-LUMO energy gap of 5.85 eV, which decreases when electron-donating groups are attached. This indicates that substitution on pyrrole through nitrogen and carbon atoms reduces the band gap, thereby enhancing conductivity. As the molecular structure grows, the increasing electron cloud raises the HOMO energy level of pyrrole. Since the LUMO energy remains constant, the band gap decreases due to the increasing HOMO value. Consequently, conductivity increases in proportion to the size of the attached structure. It is well known that increasing conjugation, that is, extending the chain length, enhances conductivity (Sahu vd. 2013; Zade vd., 2006).

Table 2. HOMO-LUMO Energy Values Calculated at the B3LYP/6-31+G** Level for $(C_4H_5N)_n$ from the Nitrogen Atom and the Carbon Atom.

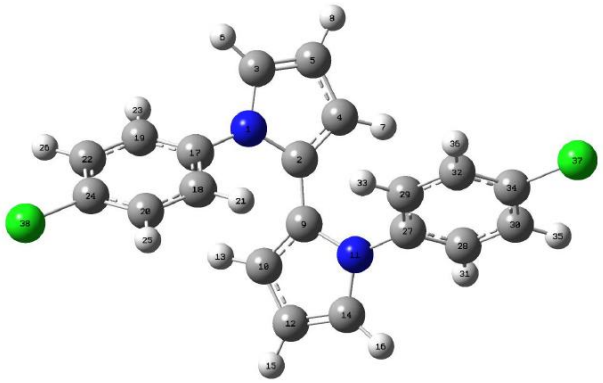
Structure	n	E_{HOMO}	E_{LUMO}	E_{GAP} (eV)
1-(4-methylphenyl) pyrrole-Cl	1	-0.226	-0.041	5.03
	2	-0.199	-0.043	4.24
	3	-0.198	-0.046	4.14
	4	-0.189	-0.047	3.86
	5	-0.190	-0.048	3.86
1-(4-methylphenyl) pyrrole-NH_2	1	-0.215	-0.025	5.17
	2	-0.179	-0.020	4.32
	3	-0.175	-0.019	4.24
	4	-0.165	-0.020	3.94
	5	-0.164	-0.019	3.94
3-(4-methylphenyl) pyrrole-Cl	1	-0.216	-0.031	5.03
	2	-0.200	-0.043	4.27
	3	-0.195	-0.053	3.86
	4	-0.189	-0.059	3.54
	5	-0.191	-0.062	3.48
3-(4-methylphenyl) pyrrole-NH_2	1	-0.198	-0.014	5.01
	2	-0.182	-0.026	4.24
	3	-0.170	-0.029	3.84
	4	-0.165	-0.035	3.54
	5	-0.163	-0.034	3.51

In Table 2, the band gap energy (E_{GAP}) values calculated at the B3LYP/6-31+G** level for 1-(4-methoxyphenyl)pyrrole and 3-(4-methoxyphenyl)pyrrole, created by adding substituents to the carbon and nitrogen atoms of $(C_4H_5N)_n$ in the presence of Cl and NH_2 atoms, decreased due to the substituent effect. It was observed that the bandgap of molecules formed by substitution at the carbon atom decreased compared to those formed by substitution at the nitrogen atom due to the effect of conjugation (n=1, 2, 3, 4, 5). However, when the chain length was n=2, the situation was reversed, and the bandgap of molecules substituted at the nitrogen position decreased. A reduced bandgap indicates increased conductivity.

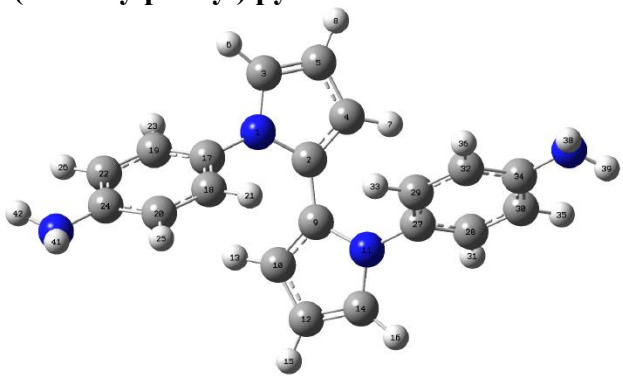
When comparing substitution at the carbon atom $(C_4H_5N)_n$ and substitution at the nitrogen atom $(C_4H_5N)_n$, based on the HOMO-LUMO energy values obtained from calculations, it can be concluded that substitution at the nitrogen atom results in a reduced bandgap energy (E_{GAP}) for $(C_4H_5N)_3$. Therefore, the 1-(4-methylphenyl)pyrrole-Cl molecule exhibits better conductivity at n=5. In the case of substitution at the carbon atom, the 3-(4-methylphenyl)pyrrole-Cl molecule shows better conductivity at n=5. When all substituents are attached to the pyrrole monomer, based on calculations at the B3LYP/6-31+G** level, it can be stated that the HOMO-LUMO energy levels are altered and conductivity increases.

The structure formed by attaching 1-(4-methylphenyl)pyrrole-Cl to the pyrrole ring exhibited a reducing effect on the energy of the highest occupied orbital compared to pyrrole. On the other hand, the structure formed by attaching 3-(4-methylphenyl)pyrrole-NH_2 to the pyrrole ring showed an increasing effect on the energy of the highest occupied orbital at n=1 compared to pyrrole.

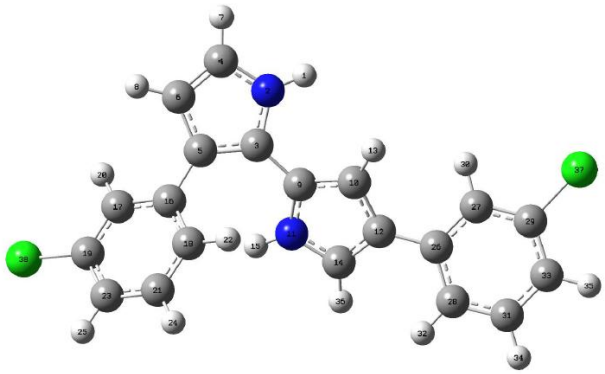
The -Cl and -NH_2 groups positively influence the valence band (HOMO) through conjugation. The energy gap between HOMO and LUMO is a measure of conductivity (Sakai vd., 1980). Based on the results, as the chain length increases from n=1 to n=5, the effects on HOMO and LUMO lead to a narrowing of the gap between the bands, resulting in improved conductivity. The reduction in the conductivity band gap may not only depend on the increase in chain length but also on substitution at the nitrogen atom. In 1-(4-methylphenyl)pyrrole and 3-(4-methylphenyl)pyrrole derivatives, when –NH_2 and –Cl are added, the Egap decreases because the HOMO increases and the LUMO decreases. The results show that substituents change the electronic structure and conductivity in π-conjugated polymers (Sahu vd. 2013; Chaudhry vd. 2013; Kon vd. 1992).



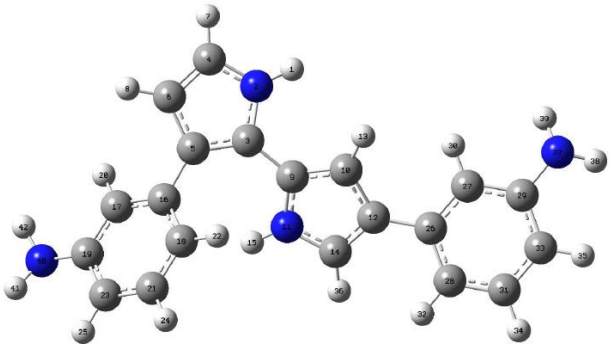
1-(4-methylphenyl) pyrrole-Cl



1-(4-methylphenyl) pyrrole-NH_2

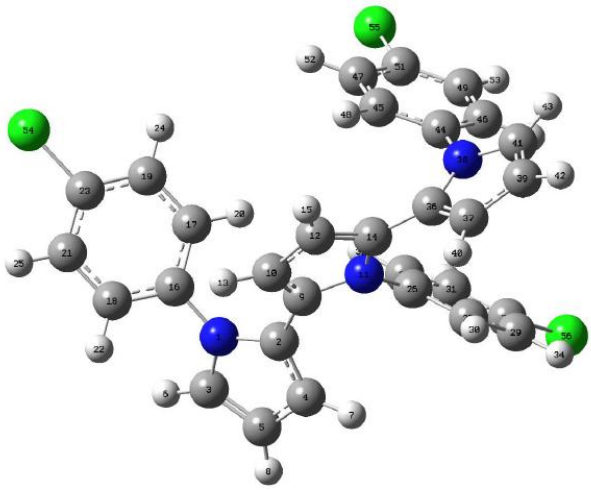


3-(4-methylphenyl) pyrrole-Cl

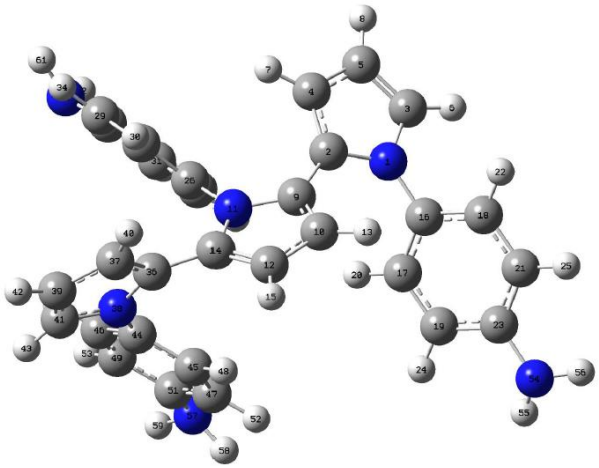


3-(4-methylphenyl) pyrrole-NH_2

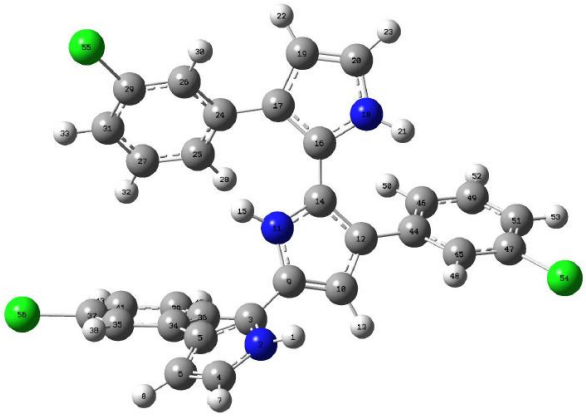
Figure 2. Dimer structures for $(C_4H_5N)_n$ from the Nitrogen and Carbon Atom



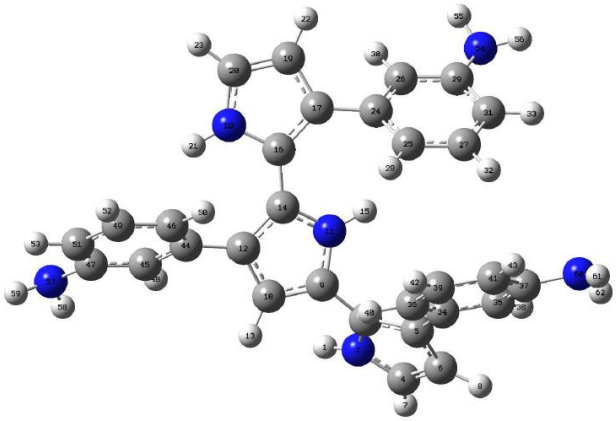
1-(4-methylphenyl) pyrrole-Cl



1-(4-methylphenyl) pyrrole-NH_2

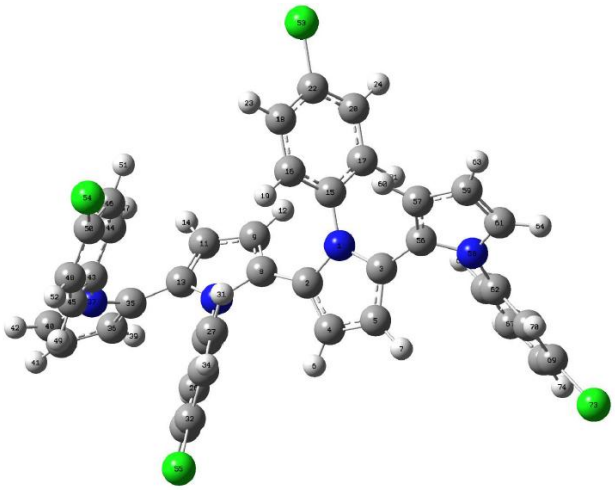


3-(4-methylphenyl) pyrrole-Cl

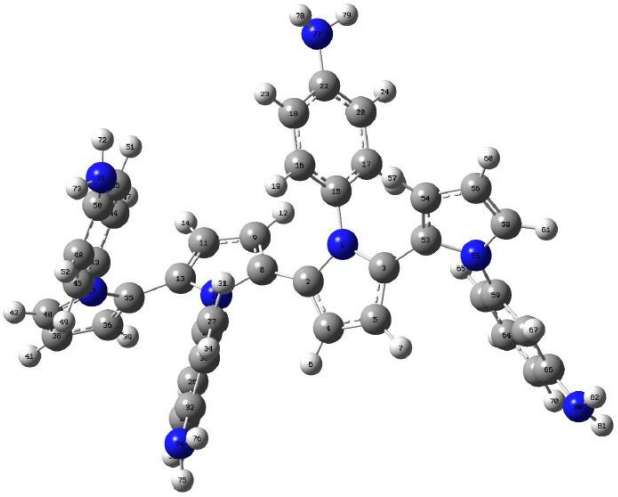


3-(4-methylphenyl) pyrrole-NH_2

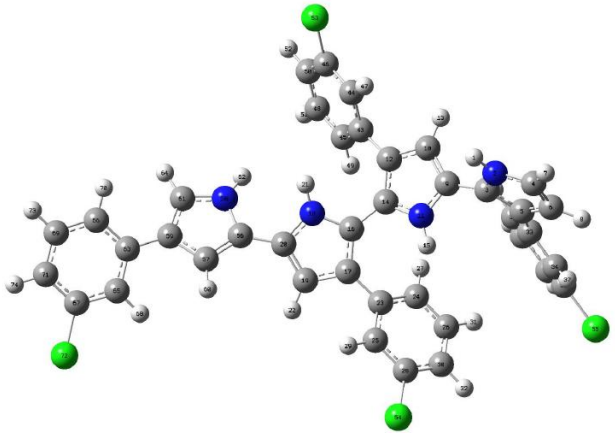
Figure 3. Trimer structures for $(C_4H_5N)_n$ from the Nitrogen and Carbon Atom



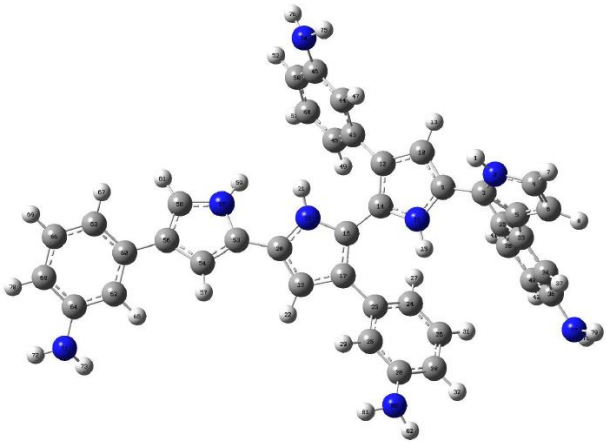
1-(4-methylphenyl) pyrrole-Cl



1-(4-methylphenyl) pyrrole-NH_2

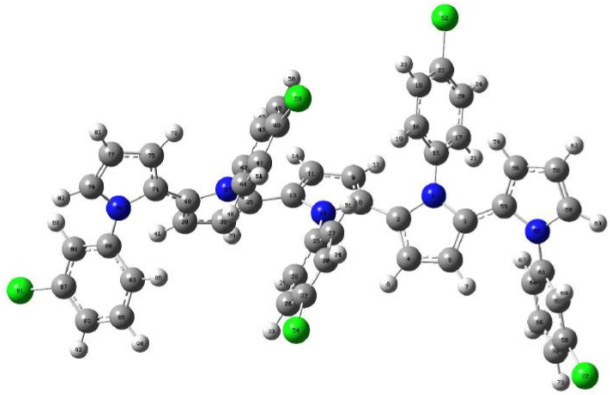


3-(4-methylphenyl) pyrrole-Cl

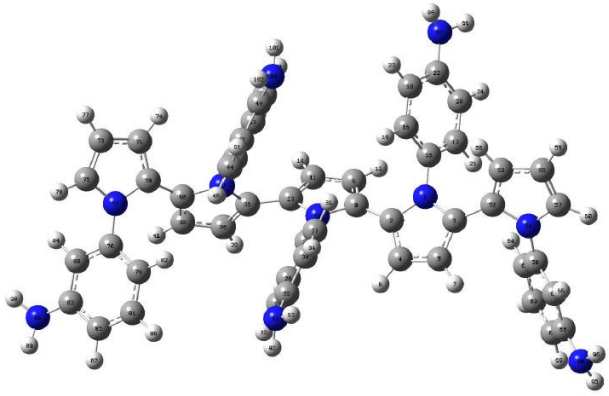


3-(4-methylphenyl) pyrrole-NH_2

Figure 4. Tetramer structures for $(C_4H_5N)_n$ from the Nitrogen and Carbon Atom



1-(4-methylphenyl) pyrrole-Cl



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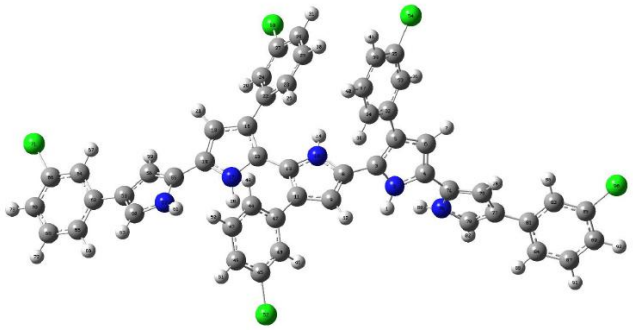
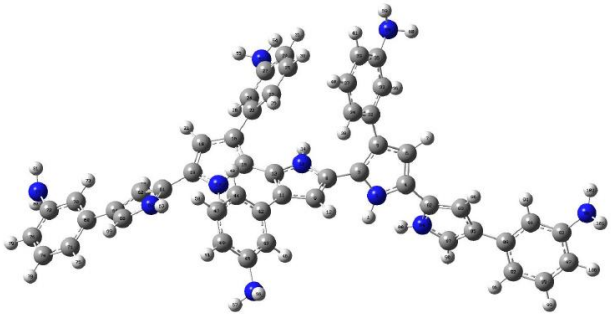


3-(4-methylphenyl) pyrrole-Cl

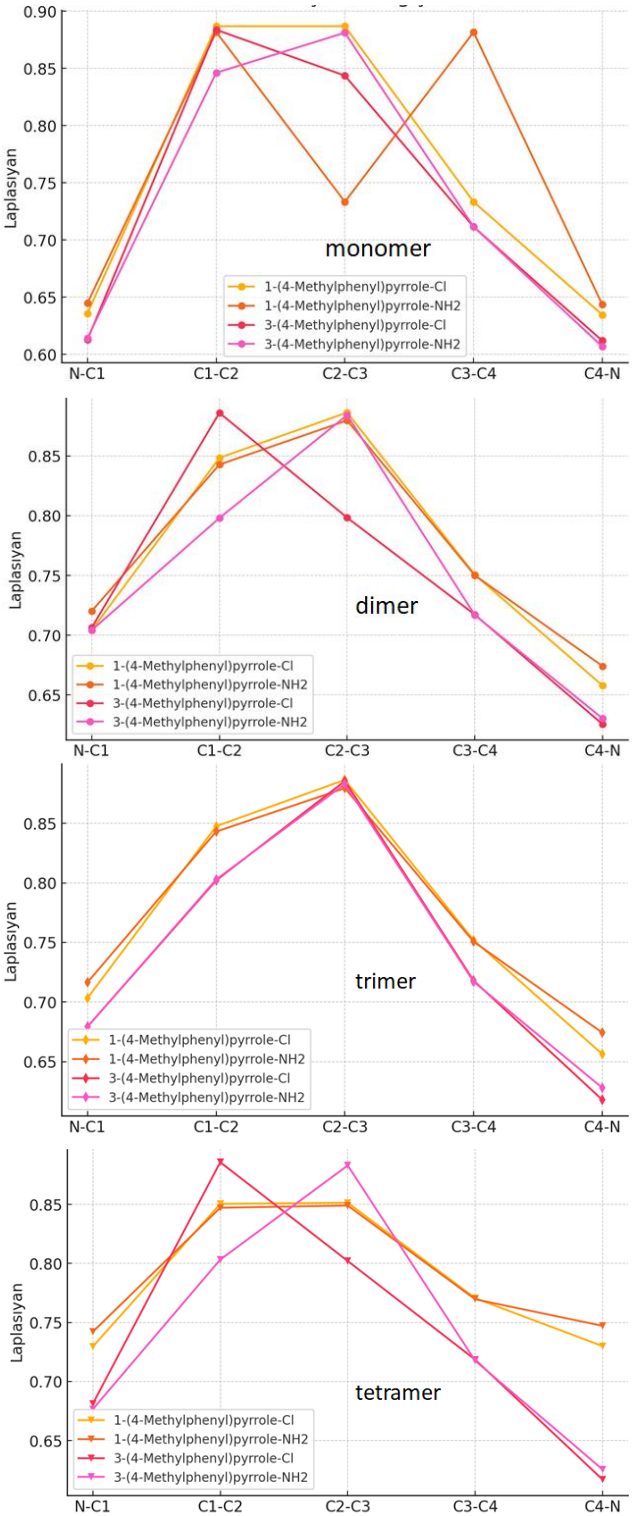


3-(4-methylphenyl) pyrrole-NH_2

Figure 5. Pentamer structures for $(C_4H_5N)_n$ from the Nitrogen and Carbon Atom

3.3. Topological Results

The structures optimized using quantum mechanical methods were subjected to electronic calculations based on the "wfn" files generated using the B3LYP/6-31+G** level of theory. These calculations were performed with the AIMAll package program. For each structure, the changes in the electronic properties of each bond in the ring were analyzed, and the values for bond critical points (BCPs) were evaluated. In general, how the Laplacian values change in consecutive bonds within the ring is shown in Figure 6.


Laplasiyan
monomer
dimer
trimer
tetramer
1-(4-Methylphenyl)pyrrole-Cl
1-(4-Methylphenyl)pyrrole-NH2
3-(4-Methylphenyl)pyrrole-Cl
3-(4-Methylphenyl)pyrrole-NH2
N-C1
C1-C2
C2-C3
C3-C4
C4-N

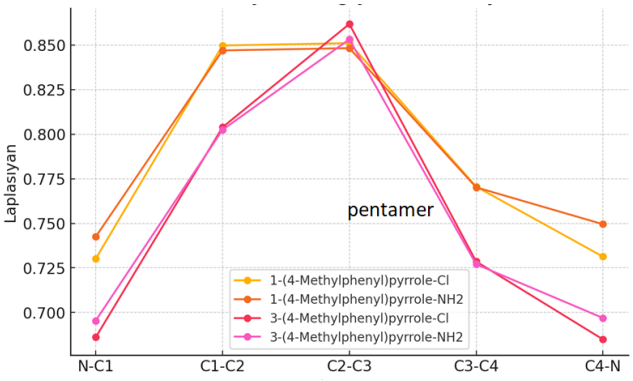


Figure 6. Laplacian Values for the 5 Bonds on the Ring (BCP) in -(4-Methylphenyl)pyrrole

When Figure 6 is examined, it is observed that the Laplacian values between N-C increase compared to the monomer when –Cl and –NH_2 groups are attached to the monomer structure. It is observed that heteroatoms influence the Laplacian values of the bonds in proportion to their conductivity values. An increasing and decreasing trend is observed in the Laplacian values of consecutive bonds within the ring. The ring critical point values of the structures formed by the attachment of electron-donating groups are presented in the Table 3-4.

Table 3. Electron Density and Laplacian Values at the B3LYP/6-31+G** Level for Nitrogen Atom in $(C_4H_5N)_n$.

		RCP	
		Electron Density	**Laplacian**
1-(4-Methylphenyl) pyrrole Cl	**Monomer**	0.048531	0.374291
	Dimer	0.048050	0.370337
	Trimer	0.048089	0.370418
	Tetramer	0.048135	0.370434
	Pentamer	0.048087	0.370422
1-(4-Methylphenyl) pyrrole NH_2	**Monomer**	0.048602	0.374422
	Dimer	0.048076	0.370463
	Trimer	0.048093	0.370383
	Tetramer	0.048169	0.370671
	Pentamer	0.048087	0.370422

Table 4**.** Electron Density and Laplacian Values at the B3LYP/6-31+G** Level for Carbon Atom in $(C_4H_5N)_n$.

		RCP	
		Electron Density	**Laplacian**
3-(4-Methylphenyl) pyrrole Cl	**Monomer**	0.048538	0.375996
	Dimer	0.048125	0.373159
	Trimer	0.048161	0.373367
	Tetramer	0.048170	0.373369
	Pentamer	0.048229	0.372118
3-(4-Methylphenyl) pyrrole NH_2	**Monomer**	0.048510	0.375521
	Dimer	0.048071	0.372677
	Trimer	0.048102	0.372648
	Tetramer	0.048114	0.372708
	Pentamer	0.048267	0.371543

For pure pyrrole, it has been observed that as the conductivity value increases, the electron density and Laplacian values decrease inversely. Similarly, it is observed here that substituents have a conductivity-enhancing effect, in other words, they decrease the RCP electron density and Laplacian values. The RCP electron density and HOMO-LUMO band gaps for carbon and nitrogen substituted molecules are presented in Table 5.

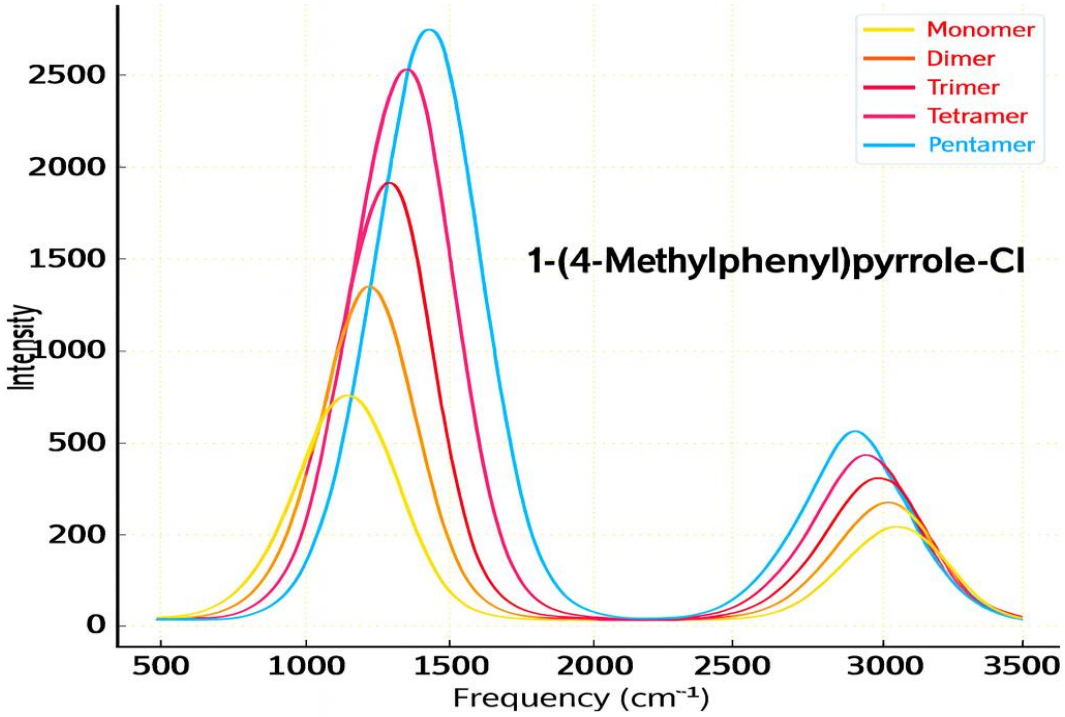
Table 5. Electron Density and HOMO-LUMO Band Gap at the B3LYP/6-31+G** Level for Carbon and Nitrogen Substituted Molecules.

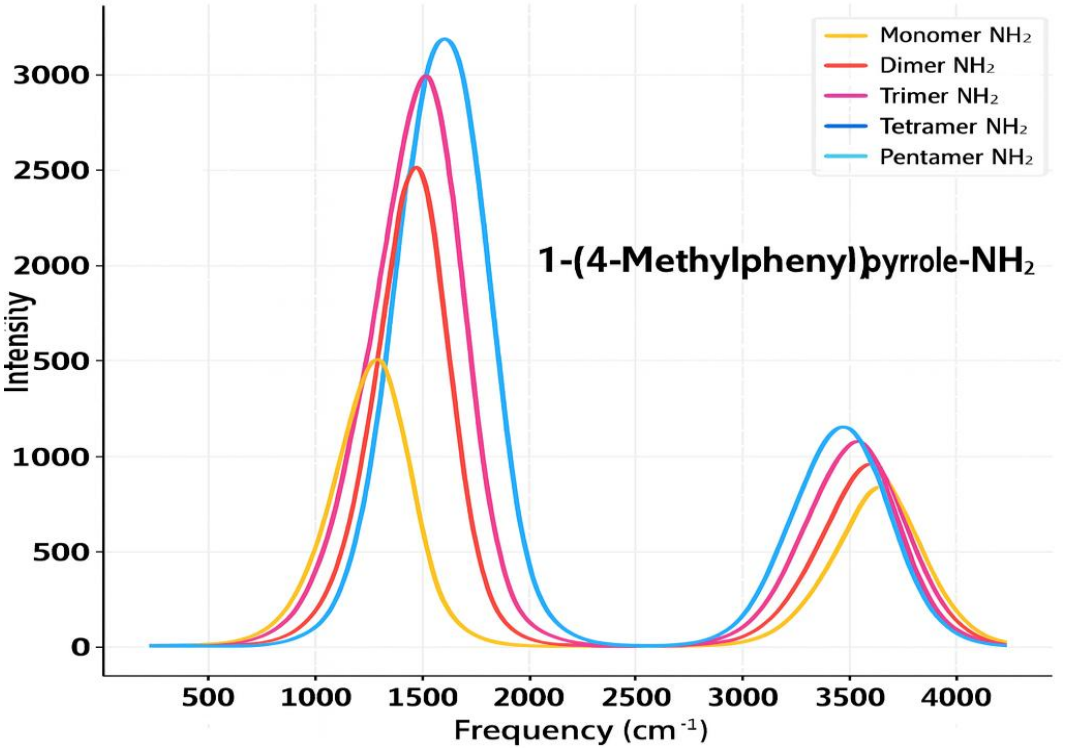
	Substituents	**RCP Electron Density**	**Band Gap (eV)**
Pyrrole	-	0.0487	5.85
Cl	1-(4-Methylphenyl) pyrrole	+0.048531	5,03
	3-(4-Methylphenyl) pyrrole	+0.048538	5,03
NH_2	1-(4-Methylphenyl) pyrrole	+0.048602	5,17
	3-(4-Methylphenyl) pyrrole	+0.048510	5,01

The ring (RCP) electron densities did not show significant changes with the increase in chain length. However, the Laplacian values were affected by the substituents, which had a reducing effect on the Laplacian value of the ring. According to the data on the HOMO-LUMO band energies of pyrrole derivatives formed by attaching -Cl and -NH_2 groups to the nitrogen and carbon atoms of pyrrole, it is observed that the energy value of 5.85 eV for the pyrrole monomer decreases when bonded from either the nitrogen or carbon atom. In both cases, the decrease in the band gap leads to an increase in conductivity. When examining the RCP electron densities, it is observed that the electron densities within the ring decrease compared to the pyrrole monomer. For the pyrrole monomer, it has been observed that as the conductivity value increases, the electron density and Laplacian values decrease inversely. The attachment of the substituent has increased conductivity and shown a reducing effect on the RCP electron density and Laplacian values. The ring critical point (RCP) electron density and Laplacian values have been shown to decrease with substitution and chain extension, with this decrease being inversely proportional to the increase in conductivity. This is consistent with findings in the literature that AIM can be used to capture bonding and topology-electronic property correlations (Prathapa vd. 2013).

3.4. Frequency Analysis

The spectra of monomer, dimer, trimer, tetramer, and pentamer are shown in different colors in Figure 7. When examining the effects of the -Cl and -NH_2 groups on the spectrum, it is observed that the intensity and position of the peak values vary depending on the degree of polymerization of the compound. In the 1-(4-Methylphenyl)pyrrole-Cl and 3-(4-Methylphenyl)pyrrole-Cl compounds, a weak C-Cl stretching band (~500 cm^{-1}) is observed at low frequencies.


Monomer
Dimer
Trimer
Tetramer
Pentamer
1-(4-Methylphenyl)pyrrole-Cl
Intensity
2500
2000
1500
1000
500
200
0
500
1000
1500
2000
2500
3000
3500
Frequency (cm⁻¹)


Monomer NH₂
Dimer NH₂
Trimer NH₂
Tetramer NH₂
Pentamer NH₂
1-(4-Methylphenyl)pyrrole-NH₂
Intensity
3000
2500
2000
1500
1000
500
0
500
1000
1500
2000
2500
3000
3500
4000
Frequency (cm⁻¹)

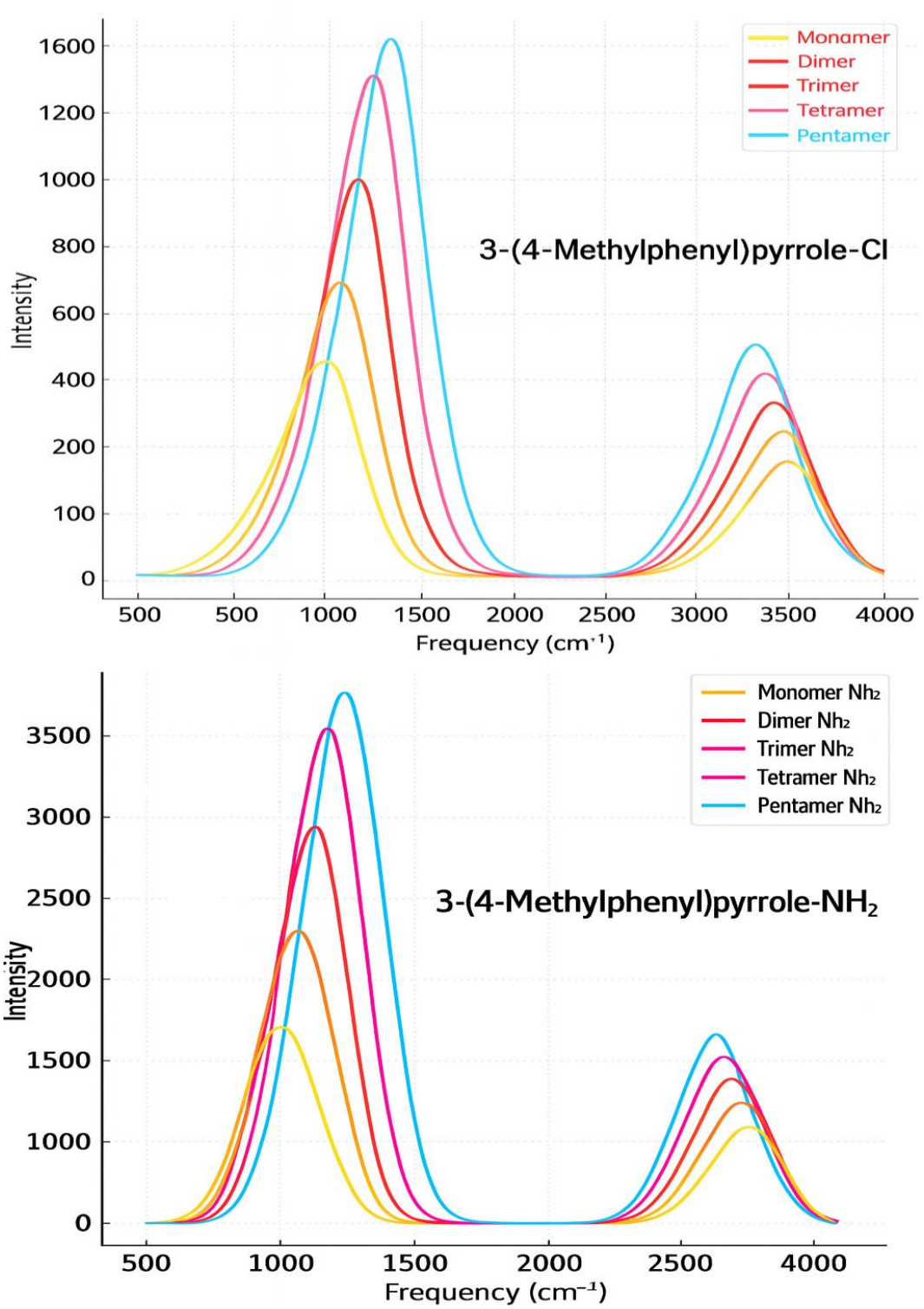


Figure 7. IR Spectra Comparison of 1-(4-Methylphenyl)pyrrole and 3-(4-Methylphenyl)pyrrole Derivatives (-Cl and -NH_2) Across Different Polymerization States

In compounds containing -NH_2, a distinct broad N-H stretching band is observed around ~3400 cm^{-1}. Aromatic C-H stretching vibrations are present in all compounds at ~3100 cm^{-1}. Aromatic C=C and C=N vibrations (~1500-1700 cm^{-1}) are prominently and intensely present in all spectra. In the pentamer form, these bands are generally observed to be more intense (especially in the blue curves).

As the transition from monomer to pentamer strengthens molecular interactions, the intensity of spectral bands increases. This effect is particularly noticeable in compounds containing the NH_2 group, where broad N-H bands become more distinct in pentamer forms. In compounds containing Cl, it is observed that low-frequency vibrations become more pronounced as polymerization increases. In 3-(4-Methylphenyl)pyrrole derivatives, more prominent vibrations are observed in the aromatic region. In 1-(4-Methylphenyl)pyrrole derivatives, sharper C-Cl vibrations are observed at lower frequencies.

4. DISCUSSION AND CONCLUSIONS

As a result of the study, it was observed that the groups reduce the band gap by increasing the HOMO energy and decreasing the LUMO energy, thereby enhancing conductivity. Additionally, when the RCP electron densities and Laplacian values were plotted against chain length for five structures (from n=1 to n=5) under the same conditions using the same monomer, it was observed that both electron density and Laplacian values decreased as conjugation increased. When examining the Laplacian values, a decreasing curve is observed for all five bonds with increasing conductivity.

The inverse relationship between electron densities and conductivity also indicates that AIM theory can be used as a tool for determining conductivity. To investigate whether the theory provides more accurate results, the study can be expanded by substituting structurally larger groups. The -Cl and -NH_2 groups cause distinct differences in the IR spectra. As polymerization increases, the spectral intensity and band width change. There are small but noticeable frequency shifts and intensity differences between the 1- and 3-isomers.

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The authors have no conflicts of interest to declare.

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LAKE EĞIRDIR UNDER GLOBAL CLIMATE CHANGE AND LOCAL PRESSURES

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Abstract: This study offers a comprehensive bibliometric analysis of Lake Eğirdir—a vital freshwater resource in Turkey—by examining the impacts of global climate change and anthropogenic activities. It aims to address key questions about bibliometric trends in lake-related research, particularly concerning global warming and other human-driven factors. The analysis draws on the Web of Science (WoS) database and was visualized through VOSviewer software to uncover publication trends and thematic clusters related to Lake Eğirdir. The results reveal a significant increase in scholarly attention and publication volume on Lake Eğirdir, particularly after 2014. Although climate change is a major contributor, anthropogenic pressures—such as agricultural expansion, pesticide use, and deforestation—play an equally substantial role in the lake's degradation. These findings highlight the need for sustained scientific monitoring and evidence-based policy actions to mitigate adverse impacts and safeguard Lake Eğirdir's ecological and economic roles. In addition to highlighting the specific challenges confronting Lake Eğirdir, this study contributes to a broader understanding of how similar freshwater systems globally are impacted by the interplay of climatic and human-induced factors. The insights gained here are essential for formulating strategies aimed at ensuring the long-term sustainability and conservation of Lake Eğirdir amid ongoing environmental pressures.

Keywords: Bibliometric analysis, Climate change, Lake Eğirdir, Water balance, VOSviewer

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1. INTRODUCTION

Freshwater ecosystems, although comprising less than 1% of the Earth's total water volume, support exceptionally rich biodiversity (Carpenter et al., 2011). However, their limited volume renders them highly susceptible to environmental changes, making them more vulnerable than terrestrial or marine systems. The mounting pressures from climate change and anthropogenic activities highlight the urgent need for comprehensive assessments of freshwater resources to ensure their sustainability and predict future risks. Bibliometric approaches have become instrumental in tracking research trends, evaluating scientific influence, and identifying emerging themes—particularly in freshwater ecosystem research (Donthu et al., 2021). These methods provide valuable insights into global collaboration patterns, environmental challenges, and thematic research gaps. One notable area in bibliometric research is the exploration of international cooperation in freshwater governance. Song et al. (2016), for example, analyzed scientific publications on the Great Lakes Region and found robust domestic collaborations but limited cross-border coordination between the U.S. and Canada. Similarly, Wang and Wang (2022) identified 14 major research clusters in the Lancang-Mekong River Basin and emphasized the importance of multilateral frameworks to address shared environmental concerns. Compared to large-scale lake systems such as the Great Lakes or Mekong Basin, Lake Eğirdir research is still developing, particularly in the realms of cross-border cooperation, long-term monitoring systems, and advanced modeling tools.

Pollution from industrial and agricultural sources has also been a recurring focus in freshwater studies. Yan et al. (2021) reported severe sediment contamination in the Yangtze River Basin, attributing it to agricultural runoff, particularly fertilizers and pesticides. Li and Nan (2017) reviewed global eutrophication research, identifying long-term nutrient enrichment as a major concern and calling for integrated management strategies. Climate change has emerged as a principal driver of biodiversity loss and ecosystem destabilization. Zhang et al. (2023) highlighted the effects of rising temperatures and prolonged drought on freshwater bodies in polar regions. In a broader scope, Williams-Subiza and Epele (2021) identified six major threats based on a review of 37,000 articles: (a) climate change, (b) water pollution, (c) river regime changes, (d) hydropower expansion, (e) invasive species, and (f) habitat loss. A growing subfield within freshwater science focuses on cyanotoxins and their impacts on ecosystem and human health. Wang et al. (2022) emphasized the dominance of microcystins in existing literature but also pointed to under-researched toxins, urging more studies on their persistence and toxicity. Building upon these findings, the present study conducts a systematic bibliometric analysis of Lake Eğirdir, a critical freshwater resource in Türkiye, to explore environmental stressors and academic research trends. While previous studies have addressed specific issues such as water quality (Sener et al., 2013), groundwater vulnerability (Sener & Davraz, 2013), eutrophication (Soyaslan & Karaguzel, 2008), and water level fluctuations (Ghorbani et al., 2018), no integrated bibliometric study has yet been conducted on this lake. In light of increasing pressures from both climate dynamics and human activity, conducting a comprehensive bibliometric review of Lake Eğirdir has become essential. Emerging themes such as the role of satellite technologies in hydrological monitoring (Yao et al., 2025), the need for international scientific cooperation (Sibandze et al., 2025), and the importance of research on understudied toxins (De León et al., 2025) are becoming central. Furthermore, freshwater science in developing countries requires stronger attention, particularly in the context of biodiversity conservation. Water recession in Lake Eğirdir, which began in the early 2000s, has accelerated in recent years (Ceylan et al., 2023). Initial studies on evaporation (Keskin & Terzi, 2006; Keskin et al., 2009) and eutrophication

(Sener et al., 2009; Beyhan & Kacikoc, 2014) laid the foundation for understanding the lake's vulnerability. Recent remote sensing studies, such as Yilmaz (2023), have shown significant surface area reductions across lakes in the region due to both climatic and anthropogenic influences. A review of the literature trends reveals that earlier studies (2006–2012) primarily focused on groundwater vulnerability and hydrological modeling. In contrast, recent publications (2018–2024) have shifted toward topics such as health risk assessment, remote sensing applications, and ecosystem-based monitoring strategies. This thematic transformation reflects both technological advancements and the growing urgency to address human health and climate-related pressures on Lake Eğirdir.

This study positions Lake Eğirdir as a case example to understand how integrated bibliometric methods can inform environmental management. The lake not only supports local agriculture and biodiversity but also serves as a critical source of drinking and irrigation water. With mounting pressures from pollution, overuse, and climate change, safeguarding Lake Eğirdir is now a regional priority. The lake hosts rich aquatic life and supports the livelihoods of communities through fishing and farming (Sekercioglu et al., 2011; Davraz et al., 2014). However, ongoing challenges such as untreated wastewater, agricultural runoff, and drought-related water level declines continue to threaten its future. Therefore, this study seeks to offer a strategic bibliometric perspective that can guide conservation efforts, inform policy, and stimulate targeted research in this ecologically vital freshwater ecosystem. Bibliometric studies on regional freshwater bodies remain rare in the global literature, particularly in the context of mid-latitude lakes like Lake Eğirdir. This study seeks to fill this gap by contextualizing the findings within broader global water governance and climate adaptation strategies.

2. METHODS

2.1. Search Criteria and Article Selection

This study investigates whether the observed decline in Lake Eğirdir's water levels—Türkiye's fourth-largest freshwater body and a crucial source of drinking water—is primarily driven by global climate change or anthropogenic activities. Through a comprehensive literature review, the study aims to evaluate the main factors influencing this trend. Bibliometric data were visualized and analyzed using VOSviewer software (version 1.6.18), enabling the identification of keyword co-occurrences, citation networks, and institutional collaborations (van Eck and Waltman, 2010). Figure 1 presents a word cloud generated from the dataset, highlighting the most frequently used keywords in publications related to Lake Eğirdir.

Figure 1. Word cloud representing the most frequent keywords in Lake Eğirdir-related publications.

An initial search was conducted in the Web of Science (WoS) database using the terms “bibliometric analysis” and “lake,” which yielded 158 records. To refine the dataset, filters were applied to include only peer-reviewed research articles within the Environmental Sciences category, limited to the SCI-Expanded index. This refinement process reduced the dataset to 22 relevant articles. A second, broader WoS search was carried out on August 9, 2024, using two independent keyword sets: (1) bibliometric analysis AND lake; (2) Lake Eğirdir. The search included only English-language research articles, with no restrictions on publication year or document type. To ensure thematic relevance, studies categorized under Social Sciences or other unrelated fields were excluded by selecting only the “Environmental Sciences” category in the SCI-Expanded index. This second search initially identified 234 records. All entries were screened for thematic relevance, and publications not directly related to Lake Eğirdir were excluded. After this screening, 45 relevant articles were retained for further analysis.

3. RESULTS AND DISCUSSION

3.1. Publication and Citations Trends

Lake Eğirdir, located at an altitude of 917 meters above sea level, is Türkiye's second-largest freshwater lake. Lake Eğirdir provides water not only to the surrounding settlements but also to agricultural areas. However, it also serves as a discharge area for both wastes from settlements and point and non-point sources resulting from agricultural activities. However, in recent years, the water level of the lake has declined from 16 meters to 4 meters, increasing environmental pressure on the lake and leading to a decline in biodiversity (Kaçıkoç et al., 2025). There are completed studies at both national and international levels focused on the

identification of pressures on Lake Eğirdir. The most comprehensive ongoing project is the "EU Partnership for Local Climate Action in Turkey" project (Yerel Iklim 2024). This project, which began on May 1, 2023, includes Lake Eğirdir in Isparta, a city in southern Türkiye, among six different cities. The project is financed by the European Union under the Instrument for Pre-Accession Assistance-III (IPA III) Funds and is implemented by the United Nations Development Programme. The European Union Delegation to Türkiye is the Contracting Authority of this project, and the final beneficiary is the Directorate of Climate Change of the Ministry of Environment, Urbanization, and Climate Change.

The number of annual publications can reflect the general trend, popularity, and development rate of a research field, as well as the interest of scientific communities in that field. We analyzed data obtained from the Web of Science database within the SCI-Exp framework from 2006 to 2024, focusing on Lake Eğirdir and environmental science themes, by examining them in annual cross-sections. The analysis was designed to reflect the total number of publications and their annual impact over the study period. The results indicate a general upward trend in the number of publications and citations specific to Lake Eğirdir in the Web of Science database from 2006 to 2024, with a notable increase particularly after 2014. The number of publications after 2014 increased by approximately 1.6 times compared to the period before 2014. This suggests that academic interest in this field has grown significantly in recent years. However, it is still believed that there are insufficient articles published on thematic areas such as global climate change, drought, unconscious water use, and uncontrolled irrigation in Lake Eğirdir. Furthermore, the number of citations in this field also showed an exponential increase after 2014 (Figure 2 (B)). This can be attributed, on the one hand, to new technologies providing new tools for research on Lake Eğirdir. On the other hand, the increasing prominence of topics such as environmental and climate change, and water resource development in recent years, has highlighted the need for in-depth and detailed research in these areas. A significant increase in both publications and citations has been observed since 2014, as shown in Figure 2. The annual changes in the number of publications on Lake Eğirdir are shown in Figure 2 (A), while the changes in citations over the years are presented in Figure 2 (B).

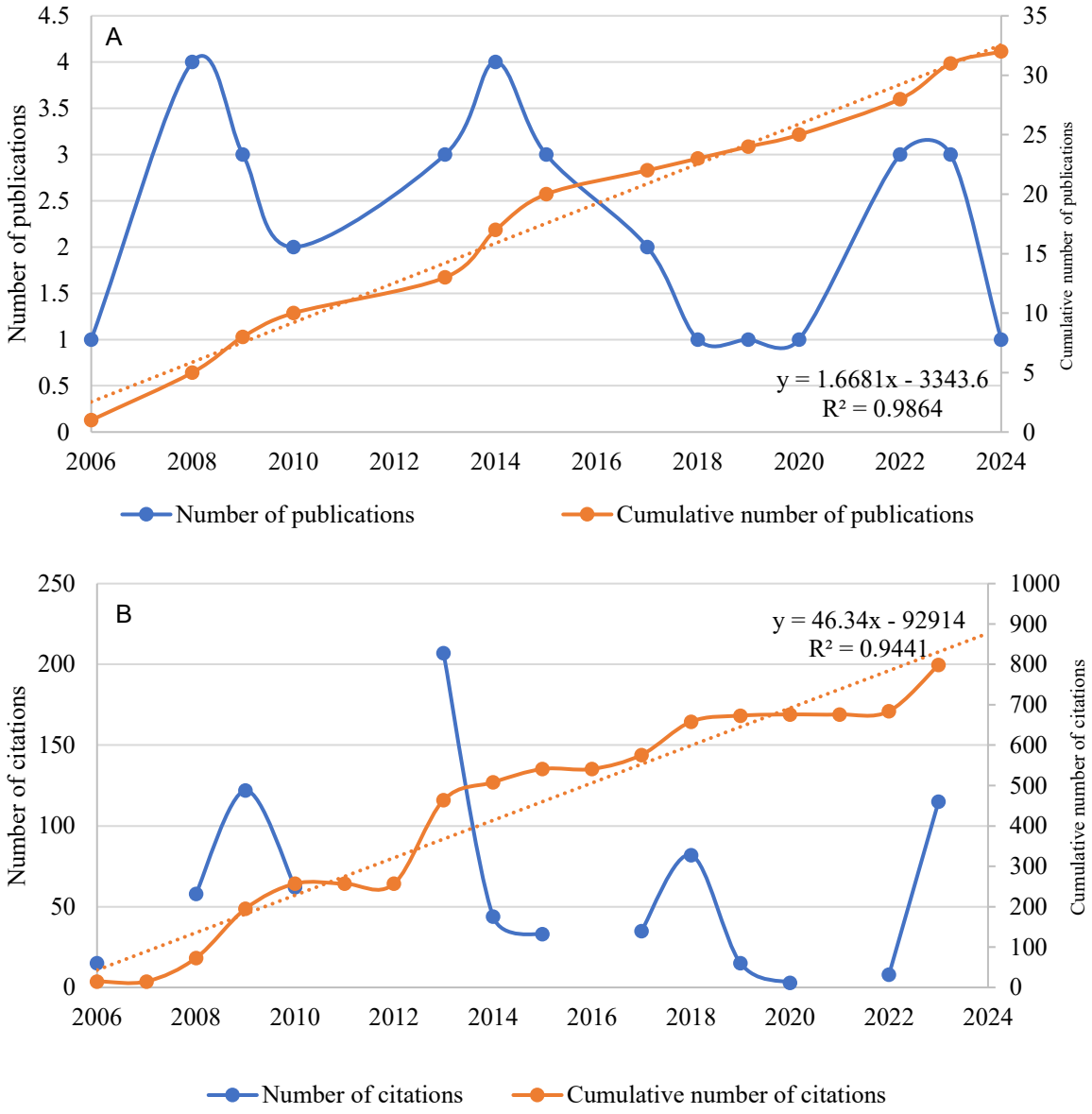

Figure 2. Annual and cumulative number of publications and citations in the Lake Eğirdir and change trends from 2006 – 2024 (A) Number of publications; (B) Number of citations

3.2. Institutions of the Publications

An analysis of the data from the top 10 university units reveals that these university units appeared in different articles a total of 41 times, contributing to 67.21% of the publications in the Web of Science database under the theme of Environmental Sciences for Lake Eğirdir. Suleyman Demirel University, which holds a leading position in Lake Eğirdir research, has published 23 articles between 2006 and 2024, accounting for 71.87% of the total publications. Suleyman Demirel University is followed by Istanbul Technical University (5 publications), Isparta University of Applied Sciences (4 publications), and the Ministry of Energy and Natural Resources (Turkey) (3 publications). All other institutions have published only one article each during this period.

The total number of citations received by the articles published by Suleyman Demirel University is 598, with an average of 26 citations per article. These values are 68 and 13.6 for

Istanbul Technical University, and 32 and 8 for Isparta University of Applied Sciences, respectively. Notably, the average publication year for Suleyman Demirel University is 2014, while for Istanbul Technical University, it is 2011. This indicates that research on Lake Eğirdir in Isparta has grown rapidly over the past decade and may have a continuously increasing scientific impact in the future.

Suleyman Demirel University, the most prolific institution in this field, has produced comprehensive research on the ecological dynamics, water quality, biodiversity, and the impacts of global warming on Lake Eğirdir. Additionally, the university's geographical proximity to the lake has facilitated fieldwork and long-term observations, enhancing the depth and scope of the research. The scientific studies produced at Suleyman Demirel University have made significant contributions to the conservation and sustainable management of Lake Eğirdir, enriching the body of knowledge in this field. In this context, the bibliometric analysis provides critical data on how Lake Eğirdir is affected by global warming and contributes to identifying threats to the lake's ecosystem and strategies to combat these threats. Moreover, these analyses play a crucial role in understanding the local impacts of global climate change and in determining the measures needed to mitigate these effects. Although Suleyman Demirel University leads in local research contributions, international collaboration remains limited. Increasing international partnerships could facilitate knowledge transfer and resource sharing, enhancing the quality and scope of research on Lake Eğirdir. Top 10 universities with the most publications in Lake Eğirdir research in the WOS database from 2006 to 2024 is shown in Figure 3.

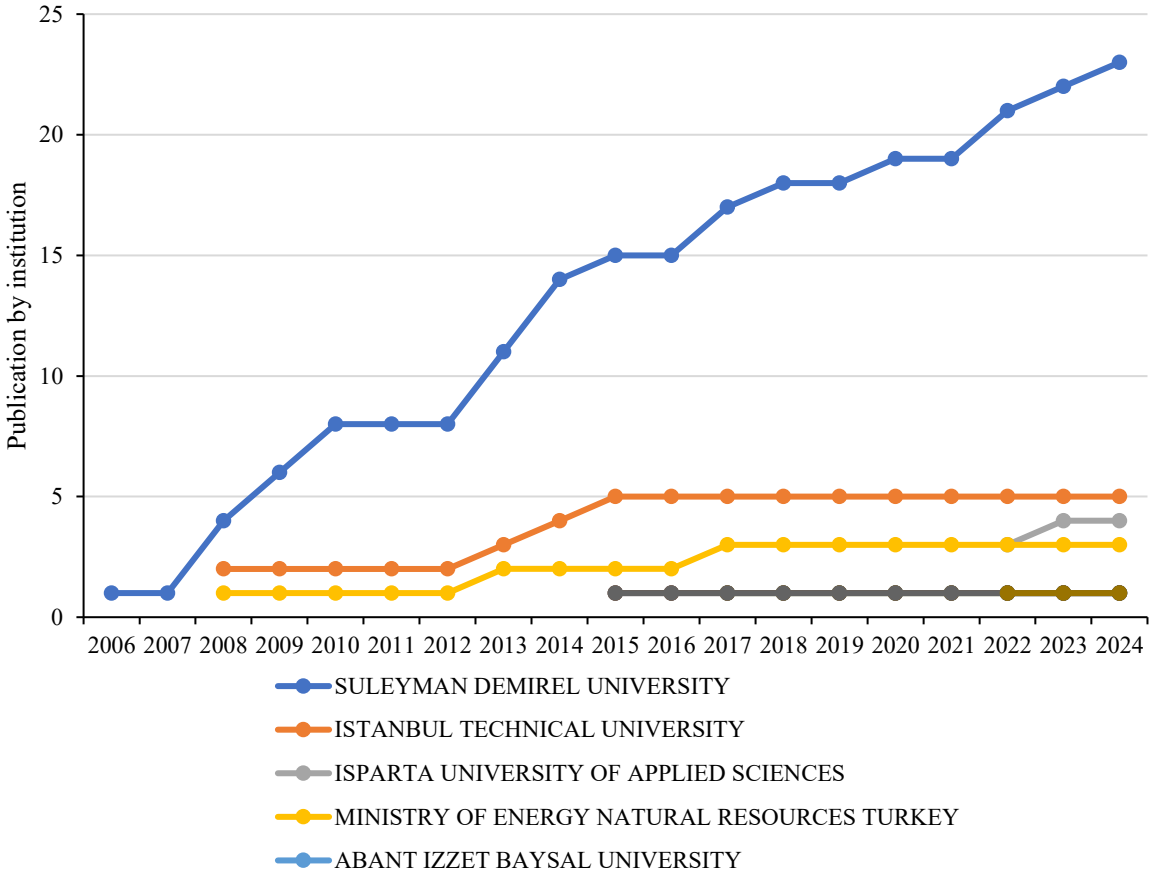

Figure 3. Top 10 universities with the most publications in Lake Eğirdir research in the WOS database from 2006 to 2024.

3.3. Citation Network Analysis

The citation network analysis was conducted using VOSviewer software to visualize connections between highly-cited papers, helping to highlight influential research and identify key authors and themes. The water quality of Lake Eğirdir has been studied for over 40 years. However, since the 2000s, water quality has begun to deteriorate, and more visibly, significant decreases in water levels have been observed. Particularly after 2010, studies completed on the lake have focused on evaporation and water levels. According to the official website of the Governorship of Isparta, "when water cannot be supplied from Lake Eğirdir, how the water needs of approximately 250,000 people living in the city center of Isparta will be met is a pressing concern (Governorship of Isparta, 2023). An analysis of the abstracts of the top 10 most-cited articles in Table 1 reveals that most of these publications focus on topics related to Lake Eğirdir, Groundwater, the DRASTIC Model, Water Quality, and Health Risk Assessment. Of these publications, five were published after 2013, indicating that most of the highly cited papers in this field have been published within the last decade.

Table 1. The top 10 most-cited publications in the field of Lake Eğirdir research

Rank	Article title	Citation frequency	Journal title	Impact factor	Publishing time	References
1	Assessment of groundwater vulnerability based on a modified DRASTIC model, GIS and an analytic hierarchy process (AHP) method: the case of Egirdir Lake basin (Isparta, Turkey)	164	Hydrogeology Journal	1.712	2013	(Sener and Davraz 2013)
2	Assessment of aquifer vulnerability based on GIS and DRASTIC methods: a case study of the Senirkent-Uluborlu Basin (Isparta, Turkey)	86	Hydrogeology Journal	1.417	2009	(Sener et al. 2009)
3	Implementation of a hybrid MLP-FFA model for water level prediction of Lake Eğirdir, Turkey	82	Stochastic Environmental Research and Risk Assessment	2.807	2018	(Ghorbani et al. 2018)
4	Comparison of Recurrent Neural Network, Adaptive Neuro-Fuzzy Inference System and Stochastic Models in Egirdir Lake Level Forecasting	54	Water Resources Management	2.201	2010	(Guldal and Tongal 2010)
5	Evaluating the anthropogenic and geologic impacts on water quality of the Eğirdir Lake, Turkey	37	Environmental Earth Sciences	1.572	2013	(Sener et al. 2013)
6	Assessment of groundwater quality and health risk in drinking water basin using GIS	31	Journal of Water and Health	1.352	2017	(Sener et al. 2017)
7	Point and non-point sources of nutrients to lakes - ecotechnological measures and mitigation methodologies - case study	28	Ecological Engineering	1.836	2008	(Gunes et al. 2008)
8	Neural network and wavelet	27	Hydrological	1.870	2009	(Kisi 2009)

	conjunction model for modelling monthly level fluctuations in Turkey		Processes			
9	Hirudinea (Annelida) species and their ecological preferences in some running waters and lakes	23	International Journal of Environmental Science and Technology	2.344	2015	(Kazanci et al. 2015)
10	Temporal variations of fluoride concentration in Isparta public water system and health impact assessment (SW-Turkey)	23	Environmental Geology	1.026	2008	(Davraz et al. 2008)

The first, "Assessment of groundwater vulnerability based on a modified DRASTIC model, GIS and an analytic hierarchy process (AHP) method: the case of Lake Eğirdir basin (Isparta, Turkey)" by Sener and Davraz (2013), evaluates the groundwater pollution potential in the Lake Eğirdir basin and identifies areas of concentrated pollution. The study mapped the contamination potential around the lake using the DRASTIC model based on the region's geological and hydrogeological features, focusing on the adverse effects of agricultural activities and other anthropogenic factors on groundwater quality. The goal was to develop strategies for protecting Lake Eğirdir.

The second most-cited article, "Assessment of aquifer vulnerability based on GIS and DRASTIC methods: a case study of the Senirkent-Uluborlu Basin (Isparta, Turkey)" by Sener et al. (2009), aims to assess the pollution potential of water resources in the Lake Eğirdir basin, particularly focusing on protecting the groundwater system in the Senirkent-Uluborlu Basin. In this study, the DRASTIC model was used to map the region's subsurface water pollution sensitivity, identifying the risk of contaminants such as pesticides and fertilizers from agricultural activities entering the groundwater.

The third most-cited article, "Implementation of a hybrid MLP-FFA model for water level prediction of Lake Eğirdir, Turkey" by Ghorbani et al. (2018), examines the application of a hybrid model, MLP-FFA, for predicting the water levels of Lake Eğirdir. This model combines the Firefly Algorithm (FFA) and Multilayer Perceptron (MLP) to provide more accurate predictions of water level fluctuations, optimized using water level data, and demonstrates superior performance compared to other models.

3.4. Literature Synthesis

Literature synthesis reveals that evaporation, agricultural pollution, pesticide contamination, and deforestation significantly impact Lake Eğirdir, with recent studies highlighting increased impacts from anthropogenic activities alongside climate-driven water scarcity. As of 2024, the water level of Lake Eğirdir has reached a critical point. The lake's water elevation has been recorded to have fallen to 914.62 meters, indicating a significant decline compared to previous years. In certain areas of the lake, the water depth has decreased to as low as 1.5 meters, and in some locations, it has even dropped to 50-60 centimeters. These conditions threaten the sustainability of both the lake’s ecosystem and its role as a water source. Additionally, factors such as evaporation and drought in the surrounding area have accelerated this decline in water levels.

Is the significant decrease in Lake Eğirdir's water level solely attributable to global climate change, or should human activities also be held responsible? This question is being addressed based on the scenarios projected in previous studies. In this section, the results from scientific papers are compiled, with a particular focus on their findings.

In a study conducted by Keskin and Terzi (2006), the dominant factors affecting evaporation in Lake Eğirdir were statistically determined to be solar radiation, air temperature, water temperature, and relative humidity. However, the decrease in the level or reduction of the water elevation of Lake Eğirdir cannot be significantly explained by evaporation alone. The water quality of Lake Eğirdir deteriorated dramatically towards the end of the 2000s.

In the study by Soyaslan and Karaguzel (2008), heavy metal pollution, particularly from pesticides used in local fruit cultivation activities, was observed. Additionally, the same paper mentioned that tannery waste in the region was also transported to Lake Eğirdir. Sener et al. (2013) identified that the sources of pollution in the Lake Eğirdir basin had negative effects on the lake's water quality. It was determined that agricultural activities posed a serious risk in areas close to the lake, and pollution loads were largely transported to the lake via four main rivers. The nutrient loads on the lake's water were found to be directly related to anthropogenic sources such as agricultural activities and wastewater discharges. Sönmez et al. (2015) highlighted that the forested areas in the region had significantly decreased between 1987 and 2006. Furthermore, open areas increased, indicating that the forested areas were destroyed due to human activities or natural pressures. The increase in agricultural activities around the lake and the expansion of irrigation practices led to the reduction of forested areas and the expansion of agricultural lands.

Sener et al. (2017) in their study showed that sources that feed Lake Eğirdir are rainfall, streams and aquifers. Lake Eğirdir and its surroundings have an important role as a source of irrigation and drinking water. The main sources of pollution include agricultural activities, uncontrolled waste management, and mining. Groundwater quality in the area is under serious threat due to the use of fertilizers and pesticides. In addition, most residential areas do not have proper wastewater treatment systems. Waste from constructed wetlands and tanneries also increases water pollution. All these factors adversely affect the quality of surface and groundwater.

Studies conducted by Yucel et al. (2022) in Lake Eğirdir show that factors such as global climate change, excessive water consumption, and unconscious irrigation lead to a decrease in water level and volume. It has been determined that the water level of the lake has experienced serious fluctuations over the years and significant decreases have been recorded especially in the periods 1969-1974, 1984-1993, 2003-2008. It is emphasized that the lake is affected by hydrometeorological variables, climatic changes and the decrease in water resources put pressure on the lake. The lake water level is generally on a downward trend, although it shows short-term increases from time to time.

Sener and Davraz (2024) reported that significant issues have emerged not only in the quantity but also in the quality of lake waters. This situation is largely associated with global climate change, with the most critical factor being the changes in precipitation patterns. Currently, an approximately 100-meter recession has occurred in the relatively shallow parts of the lake. Despite reduced water withdrawals for irrigation, the persistent decline in Lake Eğirdir's water levels appears strongly correlated with climatic factors, particularly reduced precipitation. Most of the water extracted from Lake Eğirdir is used for agricultural purposes.

According to measurable data, approximately 160 million cubic meters of water were withdrawn from the lake for agricultural irrigation in 2019 (Sener 2021). Increasing agricultural lands and rising water demands are being met by Lake Eğirdir. The annual average precipitation amounts determined by meteorological stations for the Lake Eğirdir Basin range between 790.4 mm and 501.1 mm. Satellite imagery calculations indicate that the surface area of Lake Eğirdir, which was 462.32 km² in 1987, decreased to 450.13 km² by 2021.

4. CONCLUSIONS AND FUTURE DIRECTIONS

This study underscores the ecological significance of Lake Eğirdir and its essential role in supporting biodiversity, agriculture, and local livelihoods. The bibliometric analysis reveals that the lake is increasingly exposed to both global climate change and a range of anthropogenic stressors, including agricultural runoff, pesticide pollution, and deforestation. While climate variability contributes to ecological degradation, human-induced pressures further compound these challenges. The results highlight an urgent need for targeted mitigation strategies addressing both natural and human-driven threats. Key priorities include promoting sustainable agricultural practices, implementing robust pollution control measures, and initiating reforestation and habitat restoration efforts. Continuous scientific monitoring is equally essential to track environmental changes and refine our understanding of the interconnected drivers of lake degradation. Given the escalating environmental threats, coordinated action among local, national, and international stakeholders is imperative to protect Lake Eğirdir's ecological and socio-economic value. Beyond its local relevance, the insights from this study contribute to a global understanding of freshwater system vulnerabilities and management challenges. The findings of this study align directly with SDG 6 (Clean Water and Sanitation) and SDG 13 (Climate Action), reinforcing the importance of data-driven lake management strategies. Future research should focus on understudied pollutants, especially emerging contaminants like cyanotoxins, and expand the use of advanced tools such as remote sensing, hydrological modeling, and real-time water quality monitoring. These approaches can better illuminate the dynamics between land use, water resource exploitation, and climate effects. Integrating bibliometric findings into actionable policy frameworks will strengthen conservation efforts, especially when combined with interdisciplinary strategies such as technological innovation, environmental education, and participatory governance. Ultimately, this study offers a knowledge-based platform to inform sustainable water resource management and conservation planning, contributing to the long-term resilience of Lake Eğirdir and similar freshwater ecosystems worldwide.

4.1. Policy Recommendations

In light of the findings, we propose the following policy recommendations to guide local and regional water governance efforts:

- Agricultural sustainability can be enhanced by promoting precision irrigation and organic farming incentives and buffer zones to reduce surface runoff.
- It can be strengthened through stricter monitoring and enforcement of pollution control measures, especially for agrochemicals and untreated wastewater.
- Reforestation and habitat restoration programs can be implemented in the lake's catchment area to reduce erosion and improve ecosystem services.
- A central water governance platform involving local municipalities, the Ministry of Environment, Urbanization and Climate Change, academia and local stakeholders can be

created to encourage coordinated action.

- Public awareness and engagement can be increased through environmental education initiatives and citizen science programs that target lake health.
- Secure funding and technical support can be provided for the integration of real-time water quality monitoring and remote sensing tools into regular lake management protocols.

These actions would not only improve Lake Eğirdir's resilience to current threats but also align with broader sustainable development goals and integrated water resource management principles.

Ethics Committee Approval
N/A

Peer-review
Externally peer-reviewed.

Author Contributions
Conceptualization: C.Ö.; Investigation: C.Ö., B.A.Ş.; Material and Methodology: C.Ö., B.A.Ş.; Supervision: Ş.Ş.K.B., N.A.; Visualization: C.Ö.; Writing-Original Draft: C.Ö., B.A.Ş.; Writing-review & Editing: D.A., S.Ö.; Other: All authors have read and agreed to the published version of manuscript.

Conflict of Interest
The authors have no conflicts of interest to declare.

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DETECTION OF MAGNESIUM IN SALIVA: CURRENT AND DEVELOPING METHODS

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Abstract: Identifying specific biomarkers for disease detection and using biomarkers to facilitate early diagnosis, which increases individuals' chances of survival, are among the most popular topics today. Magnesium, despite being among the most important of these biomarkers, is the least studied. These ions play a significant role in human physiological and pathological structures. Body fluids such as blood, urine, and sweat provide information about the human body. Magnesium, prominently present in saliva and abundant in the body, provides information about various pathological conditions, such as parotid malignant tumours, digitalis toxicity, chronic kidney disease, and dental enamel erosion. Information about diseases or their spread has recently become a significant source of interest due to the invasive nature of saliva and its promising potential for current clinical studies. Although numerous reviews on salivary biomarkers exist in the literature, this is the first systematic review specifically focused on Mg. This study examines the methods used to determine and quantify Mg in saliva, the studies conducted, and the results obtained. For this purpose, a systematic review of electronic databases was conducted, and studies from the last decade were reviewed, and current studies were compiled. The methods were evaluated under two main headings, each discussed separately. The health effects of the presented methods and their advantages and disadvantages are presented, providing a valuable contribution to the literature.

Keywords: Magnesium, Saliva, Health, Early diagnosis.

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1. INTRODUCTION

Early diagnosis, which increases a person's chance of survival, is associated with signals related to signs of the disease and their levels in biological fluids. The World Health Organisation (WHO) defines it as a measurement that reflects the interaction between any quantifiable element, metabolite, structure, process, or even a biological system that has the potential to affect or forecast the occurrence of diseases in the human body and potential hazard (Gug et al., 2019). The detection of these biomarkers varies according to the environment in which the detection is made (saliva, blood, etc.).

Fluids in the body, including blood, urine and sweat, provide various information about the human body. Saliva, among these body fluids, has a great place in biomedical studies with its various properties. Saliva is a water-based bodily fluid in the mouth produced by the salivary glands. Saliva, which contains 94-99% water in its composition, contains inorganic ions, secretory glycoproteins, serum elements and enzymes. Normal saliva is colourless, transparent, viscous, and tasteless (Diaz-Arnold & Marek, 2002; J. Pytko-Polonczyk1, 2017). Although the composition of saliva varies according to the body's structure, it provides information about many diseases. Saliva analysis has a wide range of applications, as it is non-invasive, can be easily collected, contains many biomarkers, can be easily stored, and maintains its stability for a long time (Woźniak et al., 2019). Hormone monitoring, detection of viruses such as HIV, hepatitis, COVID-19 (saliva-based PCR tests), diagnosis of cancer, dental health, diabetes follow-up, obesity and metabolic syndrome, DNA detection, epigenetics (Woźniak et al., 2019).

Typically, under natural conditions, Mg exists in the divalent form of Mg^{2+} and participates ionically in numerous biochemical reactions; for example, Mg is reported as a cofactor for over 300 enzymes (e.g., protein synthesis, energy metabolism, ion channel regulation). Comprehensive summaries and guides on the subject confirm this broad cofactor role (Jahnen-Dechent & Ketteler, 2012). Mg has a strong interaction with ATP: ATP molecules are often found chelated with Mg^{2+}, and the Mg ion plays a critical role in the structural stability of ATP and in many ATP-dependent enzyme reactions (e.g., phosphorus transfer reactions). This interaction highlights the indirect importance of Mg in cellular energy management(Posner et al., n.d.). Biophysiologically, antagonistic interactions between Mg and calcium (Ca) have been reported; Mg acts as a physiological Ca-antagonist by regulating membrane potential and Ca^{2+} fluxes. This antagonism has important consequences, such as in regulating smooth muscle tone, nerve, and cardiac function, and has been a long-discussed phenomenon in the literature(Jenkinson, n.d.). With the Mg ratio in saliva, important information can be obtained about diseases such as parotid malignant tumor, digitalis toxicity, chronic kidney disease (CKD), tooth enamel degradation in the mouth, cystic fibrosis, multiple sclerosis, and graft-versus-host disease (Aguiar et al., 2022; Aljerf & Mashlah, 2017) . In addition, stress lowers the level of Mg, which impacts the operation of the central nervous system (Proskurnina et al., 2023).

Figure 1, which provides a schematic representation of saliva composition and the biological role of Mg^{2+}, shows the main components of saliva. It also clearly illustrates the biological role of Mg^{2+} in saliva and the relationship between salivary components and Mg^{2+}.

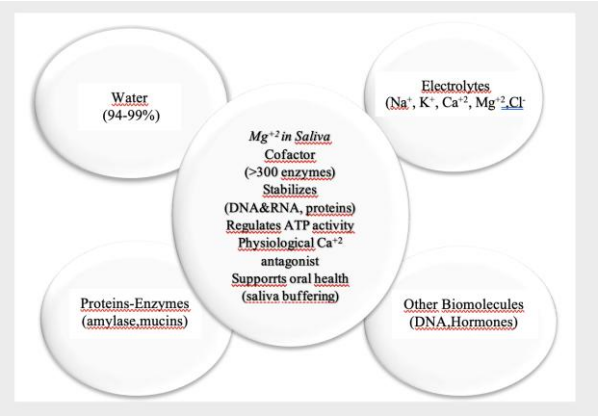

Figure 1. Schematic representation of saliva composition and the biological role of Mg^{2+}

The determination of magnesium in saliva has a long history and is gaining increasing attention in clinical and epidemiological studies (Table 1).

Table 1. Timeline of magnesium determination in saliva

Year	Method	Main Findings	Ref.
1935	Dialysis / adsorption (early chemical assays)	Early physicochemical studies reported calcium, phosphate, and magnesium in saliva; methodological limitations.	(Knox & Still, n.d.)
1955	Simple photometric / chemical methods	Practical methods for Ca and Mg determination in saliva were introduced; first standardized measurements.	(Ericsson, n.d.)
1965	Atomic Absorption Spectroscopy (AAS)	Mg levels have been shown to increase in paraffin-stimulated saliva.	(Gow, n.d.)
1968	AAS + ultrafiltration	Stimulated vs resting saliva fractions analyzed; Mg and Ca levels measured.	(Lear & Grin, 1968)
1979	Parotid saliva, flow rate, chemical assays	207 children: higher caries index linked to reduced Ca and P; Mg also decreased but less markedly.	(Shannon & Ralph Feller, 1979)
1994	Whole saliva / trace elements	The prevalence of dental caries in young adults is associated with salivary Zn, Cu, Ca, and Mg..	(Borella et al., 1994)
2018	Serum & saliva (Xylidyl blue method)	Mg levels significantly lower in OSCC patients compared to controls; potential biomarker role.	(Aziz et al., 2018)
2022	Salivary Mg in OSCC patients	Compared to controls, Mg differences were not consistently significant; mixed findings.	(Shekatkar et al., 2022)
2023	Calmagite method; serum vs saliva	In individuals with tobacco habits, Mg decreased with progression to potentially malignant disorders.	(Singhal et al., 2023)
2024	Serum & saliva (OSCC/OPMD vs controls)	Ca and Mg altered in OSCC/OPMD groups compared to healthy controls; Mg generally reduced.	(Samadi et al., 2024)
2024	Cross-sectional (IBD patients)	Inflammatory bowel disease patients showed significantly lower serum and salivary Ca & Mg vs controls.	(Mirzaii-Dizgah et al., 2024)

Liquid chromatography coupled with mass spectrometry (LC-MS) and ultraviolet-visible (UV-VIS) spectrophotometry, enzyme-linked immunosorbent assay (ELISA), electrophoretic immunoassay, radioimmunoassay (RIA), mass spectrometry-based proteomics, and DNA-based methods, microchips and microfluidic devices, and electrochemical biosensors are included in saliva biomarker detection (Gug et al., 2019). For Mg biomarkers, electrochemical, spectroscopic or biochemical analysis methods are generally used, but atomic absorption

spectrometry (AAS) and ion-selective electrode (ISE) methods, fluorometric methods, ion chromatography (IC), voltammetric methods, chemosensors, inductively coupled plasma mass spectrometry (ICP-MS) and electrochemical techniques are used. These demonstrate the methodological diversity and the application potential of Mg determination in saliva (Table 2).

Table 2. Comparison of Mg determination methods

Method	**Adv.**	**Disadv.**	**LOD/ LOQ**	**Ref.**
AAS	High accuracy, reproducibilit; widely used standard method	Requires laboratory setup; time-consuming; skilled operator needed	µg/L	(Welz & Sperling, 1998)
ICP-OES/ MS	Multi-element analysis; very high sensitivity	Very expensive instruments; requires expertise; non-portable	ng/L	(Welz & Sperling, 1998)
Colorimetric Kits	Simple, rapid, low-cost; suitable for field applications	Relatively low sensitivity; potential interference effects	~40 µM	(Lewińska et al., 2024; Malahom et al., 2017)
ISE	Fast measurement; real-time detection	Limited accuracy; frequent calibration required	µM	(Bakker et al., n.d.)
Biosensors (enzyme/ aptamer-based)	High specificity; can be miniaturized; potential for field and clinical use	Stability and production cost issues; many still under development	nM–µM	(Guo et al., 2021; Stangherlin et al., 2025; Xu et al., 2023)
Microfluidic Paper-based Devices (µPADs)	Very low sample volume; low cost; rapid analysis	Fabrication techniques still under optimization; calibration may be required	µM	(Yetisen et al., 2013)

When we look at the reviews conducted to date, almost all of these studies aim to detect biomarkers in saliva. Saliva-based biomarker studies have generally focused on various analytes such as hormones, proteins, and nucleic acids (Gug et al., 2019; Woźniak et al., 2019). The need for the development of new techniques and methodologies for the determination of Mg in saliva is evident. However, despite magnesium (Mg) being one of the most critical cations for physiological functions, there is no review of studies specifically focused on the determination of Mg in saliva. Previous reviews have superficially addressed Mg as part of broader biomarker assessments or focused on its measurement in blood and serum samples (Diaz-Arnold & Marek, 2002; Ilea et al., 2019). This study, which stands out in many ways, fills this gap by systematically analyzing Mg determination in saliva, discussing both traditional and emerging techniques, and highlighting the clinical implications of measuring Mg in this biofluid. Its focus has established a rhythm in the literature. The methods are discussed, their advantages and disadvantages are discussed, and their effects on health development are attempted to be revealed.

2. MATERIAL - METHOD

This study compiled the literature on magnesium using a systematic review method. The screening process was carried out as follows:

A comprehensive literature search was conducted using PubMed/MEDLINE, Scopus, and Web of Science databases. Additionally, Google Scholar was used to identify open-access resources that were not indexed in primary databases. The search aimed to include the oldest studies on magnesium determination in saliva and the latest advances in biosensor technologies, particularly on studies conducted within the last 10 years. "Magnesium", "Mg^{2+}", "enzyme cofactor", "DNA stabilization", "ATP", "calcium antagonism", "Salivary magnesium," "salivary ions," "magnesium biosensors," "μPAD magnesium determination," "salivary electrolytes," and "analytical methods for salivary Mg" were used as search terms in the study. Boolean operators (AND/OR) were applied to maximise coverage. The types of studies are clinical, experimental, and in vitro studies. The study included (i) original research articles, (ii) studies reporting methods or technologies for the detection of magnesium in saliva, (iii) publications in English, and (iv) articles published between 2000 and 2025. (i) non-peer-reviewed sources, (ii) studies not explicitly related to magnesium in saliva, and (iii) conference abstracts without full text were excluded. After identifying relevant studies, articles were categorised for each method. The articles were reviewed in full text and evaluated under separate headings.

Which method will be used for the detection of Mg in saliva may vary according to the parameters of analysis sensitivity, cost, speed and laboratory facilities. While most of the studies were to identify various substances present in saliva (Ilea et al., 2019), it was observed that a limited part of them were focused on identifying Mg within saliva. The information obtained as a result of the searches made in electronic databases was evaluated and collected under 2 headings: detection methods, laboratory-based methods and methods under development.

2.1. Laboratory-Based Methods

Test kits, AAS, ICP-MS, and ion chromatography are among the laboratory-based methods.

First of all, when we look at the studies carried out with test kits, the study was based on the idea that exercise may lead to alterations in the biological indicators in saliva, and the selected saliva components were compared in swimmers before and after training. Of the 40 boys between 12 and 15, 30 were swimmers, and 10 were part of the control group. Saliva samples were taken from all participants in the morning and afternoon, and samples from swimmers before and after training. In the study, various parameters were measured, and a significant increase in Mg values was observed in swimmers following the morning exercise and after training in the afternoon. As a result of the study, it was concluded that magnesium levels were related to swimming training session (Grzesiak-Gasek & Kaczmarek, 2022).

Three groups were studied in which magnesium was estimated in serum and saliva. Groups studied: patients who use tobacco habit but not potentially malignant disorders, patients with tobacco habit as well as potentially cancerous conditions, and the control group. Mean saliva Mg levels were 1.442 mg/dl, 0.551 mg/dl and 0.463 mg/dl, respectively (Singhal et al. 2023). Enzyme-linked immunosorbent assay (ELISA) is the benchmark for biomarker identification and quantification in saliva (Pandit et al., 2024). However, the study in which the detection of

Mg was made with ELISA is quite limited. In a study involving 42 type II diabetic patients between the ages of 40 and 60 and 45 healthy controls without underlying systemic disease, the levels of saliva trace elements were evaluated using colourimetric and Ethylenediaminetetraacetic acid tests. It is stated that there exists a slight negative correlation between salivary magnesium and copper levels and CFU/ml, but this correlation is not statistically meaningful. Furthermore, it is stated that the mean saliva Mg concentration was 0.02121 ± 0.00445 in the study group, whereas the average concentration was 0.00062 ± 0.00006 in the control group (Mohammed et al. 2024). The disadvantage of the ELISA method is that it consists of many time-consuming steps, is expensive, and enables the examination of a single protein per plate (Gug et al., 2019).

Twenty subjects were included in the study, which evaluated stress biomarkers and electrolytes in the saliva of individuals receiving fixed orthodontic treatment. Saliva samples were collected at three different times, and Mg concentrations of electrolytes were evaluated using commercial kits. As a result of the study, when the saliva electrolyte composition was evaluated in the patient and control groups, it was stated that magnesium concentrations were similar in these groups (Silva Andrade et al., 2018).

AAS is a highly sensitive and accurate method for detecting Mg ions in saliva. The light absorption makes the detection of Mg atoms possible. To analyze the saliva sample, Mg ions are brought into atomic form by burning them in a flame or graphite furnace, and the concentration is calculated by measuring the amount of light absorption of Mg atoms at a specific wavelength. In the study, in which sodium (Na), potassium (K), Mg and Ca in human saliva were directly analyzed and their relationships with physiological states were examined, it was determined that the linear range for Mg was 0.0-0.5 mg/L and the LOD value was 0.5 mg/L. This study, which used the direct analysis method, stands out because chemicals were not used (dos Reis et al., 2020).

In the study using electrothermal atomization atomic absorption spectroscopy, it is stated that saliva Mg and parameters related to antioxidants can provide valuable insights in the examination of Generalised Anxiety Disorder (GAD). The study included 15 patients with GAD and 17 healthy individuals as volunteer control subgroups of the same age. Participants were subjected to a test at six difficulty levels, including false feedback. Participants were instructed to recall the colours of the balloons and respond when the colour shifted. The reaction time was interpreted by evaluating biochemical factors, including the antioxidant capacity of saliva and salivary magnesium levels, using the number of correct answers. It is stated that the Mg levels in saliva are elevated in patients with GAD than in the control group (Proskurnina et al., 2023).

In the study, which aimed to examine the connection between blood and salivary magnesium levels and pain characteristics and anxiety-depression scores in patients with migraine, 40 patients with migraine and 30 people without pain complaints as a control group were included in the study. The study concluded that saliva mg levels were reduced compared to the control group in both the attack and initiation periods. However, this low level was not related to pain characteristics. In addition, it has been stated that the initial and attack blood mg levels of patients with migraine are significantly lower than those with a long history of the disease (Altunkaynak et al., n.d.). Forty-two subjects used the study to compare gum health conditions and salivary magnesium levels in smokers and non-smokers. Saliva Mg levels were measured with AAS, and Mg levels were found to be 54.43±17.37 and 51.29±15.97 mg/dl in smokers and non-smokers, respectively (Wijaya et al., 2021).

ICP-MS involves ionizing the saliva sample, and Mg ions are separated by mass. With this method, even very low magnesium levels can be detected. In the study, in which individuals with type 2 diabetes were compared with a control group consisting of healthy subjects to analyze the levels of Mg, Ca, and zinc (Zn) in saliva, it was stated that the concentrations of Zn, Ca and Mg were significantly higher in the diabetes group than in the control group. In addition, it was noted that a relationship in ICP-MS involves magnesium levels in saliva ($p = 0.003$) in men. It is also among the results of this study that Mg, Ca and Zn levels in saliva may be useful markers to distinguish individuals with type 2 diabetes from those without diabetes (Marín Martínez et al., 2018).

In the study in which trace element levels in saliva were determined by ICP-AES in Oral Lichen Planus (OLP), a prevalent inflammatory condition of unknown origin, a study was conducted on 40 patients and 40 healthy individuals. As a result of the study, it was stated that Mg levels were notably reduced in patients with OLP compared to healthy controls, and there was no significant difference between erosive and non-erosive Lichen Planus types (Rezazadeh et al., 2019). In the study titled "The relationship between certain macro and trace elements in saliva and periodontal health", ICP-MS was used to determine the levels of the elements. A total of 190 systemically healthy, non-smoking participants (mean age 32.2 ± 6.02 years; 50 periodontally healthy controls (H), 50 patients with gingivitis (G), 50 patients with chronic periodontitis (CP) and 40 patients with disseminated aggressive periodontitis (GAP) were included in the study. As a result of the study, it was found that there was a significant difference in Mg concentrations between the groups, and that significant increases were observed in Mg, which is an essential mineral, ın both periodontitis groups, compared to the gingivitis group and periodontal healthy groups (Inonu et al., 2020).

Saliva samples from 66 healthy non-smokers (20 periodontally healthy, 24 untreated severe periodontitis, and 22 treated severe periodontitis patients were analysed using ICP-MS in the study, which aimed to compare the connection between mineral elements in saliva and periodontal health in patients with treated and untreated periodontitis with periodontally healthy controls. In healthy controls, Mg levels in saliva were found to be 6.31 ± 0.59 mg/L, 7.67 ± 1.013 mg/L, and 6.125 ± 0.78 mg/L in untreated periodontitis and treated periodontitis (Romano et al., 2020).

In the ion chromatography method, in which Mg is measured by separating it from other ions, the concentration is determined by separating the Mg ions in the saliva sample from other ions using chromatographic columns. It has the advantages of high solubility and specificity, being suitable for use in complex biological fluids. In the study, where the piezoelectric quartz crystal (PQC) detector was created and the Calcium (Ca^{2+}) and magnesium (Mg^{2+}) levels in human saliva and urine were determined by ion chromatography, some samples were also determined by the AAS method. The t value obtained in the method used was 3.42 for Mg in saliva (Yu et al., 2001).

2.2. Methods Under Development

ISE, chemosensors, microfluidic-based structures and biosensors are included in this heading.

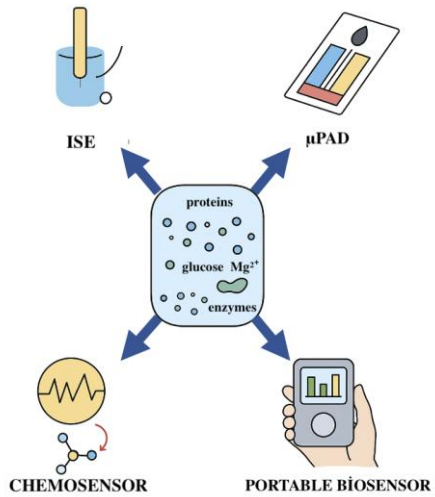

Figure 3. Illustration of methods under development

It is based on the principle that ion-selective electrodes detect a specific ion through a selective membrane. Electrodes that selectively detect magnesium ions in saliva provide fast and practical analysis. Different electrodes can be used, such as graphite electrodes or screen-printed electrodes. It is easy to apply, gives quick results, and can be done with portable devices. The study shows the possibility of using ISEs for ionic component changes in saliva in saliva samples by determining various ion concentrations, such as Sodium (Na+), potassium (K+), calcium (Ca^{2+}), magnesium (Mg^{2+}), and chloride (Cl-) using glassy carbon-based ISEs and a sensor platform with glassy carbon electrodes. It is also noted that there is a connection between the type and intensity of body stimulation and the ion concentration (Urbanowicz et al., 2017).

In another study in which salivary magnesis levels were estimated ın individuals with oral squamous cell carcinoma, it was stated that impaired Mg homeostasis would lead to pathological conditions. Based on the change in the level of Mg in saliva in patients with cancer, a study was conducted on 36 people, 18 of whom were sick. While the Mg level was 0.4333 mg/dl in the control group, this level was 0.5778 mg/dl in patients (Shekatkar et al., 2022).

Chemosensors create signals by interacting with magnesium ions. In addition to being usable for detecting Mg in biosensors and similar devices, it is sensitive and portable. µPADs stand out with their ability to enable on-site detections, trained operators and the fact that they do not require special laboratory equipment. In the study, in which a microfluidic paper-based analytical device (µPAD) was created for the determination of Mg in saliva samples, magnesium standard solutions within the range of 0.082-0.247 mM were prepared with synthetic saliva and Bovine serum albumin (BSA), and the colour intensity was measured through image processing. The limits of detection and quantification are 62 µM and 81 µM, respectively (Aguiar et al., 2022).

Biosensors, simply put, are analytical devices consisting of a bioreceptor, a transducer, and a signal processor for identifying molecules (Rezazadeh et al., 2019). They consist of two main components: a bioreceptor and a transducer. The bioreceptor is responsible for analyte recognition and the sensor's broad specificity and sensitivity. They can bind to a specific

substrate and are categorised into three groups: enzyme-based, whole-cell-based, and bioaffinity-based (Mehrvar et al., 2000). Biosensors are widely used in various fields such as health monitoring, environmental analysis, food safety, etc. Various transducers, such as electrochemical transducers, optical transducers, and piezoelectric transducers, can be used in its structure, and the sensors take different names according to the transducer structure used. Electrochemical sensors, a type of biosensor, are widely used in clinical applications for detecting biomarkers in saliva, their effectiveness, and diagnostic/therapeutic applications due to their low cost and fast analysis features (Zheng et al., 2021). The electrical changes caused by Mg ions on the electrode are detected. Fast and low-cost, it can be applied in portable devices.

When the literature is evaluated, it is observed that several studies exist involving biosensors and Mg duo. For example, in biosensor studies where saliva-based or saliva-based biomarkers can be detected, it is seen that the detection of lactate, glucose, phosphate, salivary hormones, etc., is emphasized (Malon et al., 2014). In many studies, Mg stands out as a component used in producing biosensors rather than being an analyte to be detected by biosensor structures (Kao et al., 2017; Vladimirov et al., 2014; Yang et al., 2023). The most important conclusion to be drawn from this is the necessity of contributing to the literature in this field.

A microfluidic paper-based analytical device (μPAD) has been developed to determine magnesium in saliva samples. This device is based on the principle of magnesium forming a colored complex with eriochrome cyanine, and analysis is performed by measuring colour intensity using digital scanning. The device has a lower detection limit of 62 μM, providing a user-friendly solution that does not require laboratory equipment (Aguiar et al., 2022). The integrated microfluidic immunosensor device combines vibration-accelerated incubation and magnetic separation technologies. This device is designed for rapid and sensitive biomolecule detection and can be used in biological samples such as saliva(Liang et al., 2025). Artificial intelligence-supported biosensors have been developed to assess the homogeneity and stability of sodium, calcium, magnesium, and manganese ions in saliva. These sensors play an important role in the detection and analysis of biomarkers(Constantin et al., 2025).

These studies demonstrate the diversity and advancements in biosensors and microfluidic systems developed for detecting magnesium in saliva samples. These technologies are expected to be further developed and widely used in clinical applications in the future.

Table 3. Comparison of under development methots

Method	Adv.	Disadv.	LOD	Detection Time	Portab.	Ref
µPAD	No laboratory required, low cost, user friendly, fast and practical	Possible error in color measurement, limited accuracy, analysis time may be long under some conditions	62 µM	10–90 min	High	(Aguiar et al., 2022)
Integrated Microfluidic Immunosensor	Fast, accurate, low-cost, portable	Limited mechanical durability, sensor life may be shortened, manufacturing process may be complicated	0.57 µM	5 sec	Medium	(Wang et al., 2025)
Smartphone-Based Biosensor	Portable, user-friendly, digital data recording	Variation in color measurement due to camera, limited sensitivity	50 µM	1 min	High	(Awad et al., 2025)
AI-Supported Biosensor	Multi-ion detection, strong data analysis capability	Requires AI model training, relatively expensive	–	–	Medium	(Constantin et al., 2025)

3. CONCLUDING REMARKS AND FUTURE PERSPECTIVES

Determining the concentrations of various minerals, elements, enzymes and hormones in human body fluids in a short time with high sensitivity plays a crucial role in detecting and evaluating the disease. This situation has brought with it a continuous increase in the need for advanced technology and sensitive analysis methods. In addition to the increase in the variety and number of diseases, the proportional rise in cancer and psychological disorders underlines that the need for this situation is gaining importance day by day. Determination and monitoring of Mg in body fluids is significant because there is currently no quick and straightforward test to assess total body magnesium.

Saliva has important advantages with its features of being non-invasive, painless, easy to sample, low cost, and not requiring long processing. Considering its content, saliva is promising in the early detection and management of many diseases.

Based on all these cases, this study highlights the methods and developments in magnesium detection in saliva. The magnesium detection methods reviewed in this review have the potential to measure magnesium with high sensitivity, particularly in saliva and other biological fluids. A brief evaluation of the studies in the literature is presented in Table 4. While existing methods provide reliable results in the laboratory setting, some challenges remain regarding integration into clinical practice. For example, the complex instrumentation requirements and long analysis times of traditional techniques limit their use in routine patient care. Laboratory-based methods have many processing steps, require expensive and complex devices, and do not provide results that enable rapid, sensitive, and early diagnosis. Furthermore, the requirement for short-term storage at specific temperatures in saliva to prevent degradation remains an unresolved issue. In the future, portable biosensors may be critical for magnesium monitoring

in clinical practice. Such devices can support individual health management by providing fast and accurate data at the patient's bedside and in remote healthcare settings. Portable devices will have a significant impact, particularly in chronic disease monitoring, nutritional assessment, and athletic fitness monitoring. Research gaps focus on clinical validation, data standardisation, and accessible portable device design.
It is known that more sensitive determinations are needed, such as the determination of magnesium, a biomarker in saliva. In this regard, biosensor structures often come to the fore. This necessitates designing and implementing green biosensors that will not harm the environment and allow for rapid, sensitive, and cost-effective detection. This will facilitate disease diagnosis and monitoring while contributing to the development of healthcare services. Easier sample collection in the elderly and children will enable large-scale screening.

Unlike previous studies, this review focuses solely on determining Mg in saliva, whereas in previous studies, it was treated as a secondary analyte. By systematically compiling and comparing existing methods, our study offers a unique perspective not previously addressed, thus contributing to the literature.

Furthermore, developing environmentally friendly biosensors is important for cost and sustainability. Replacing traditional sensor materials with biological or biodegradable components will provide ecological advantages for laboratory and field use. This approach will increase the applicability of biosensor technology not only in the healthcare sector, but also in environmental monitoring and food safety. Standardisation and validation efforts should be increased to ensure reliable operation of sensors in hospital and home environments for clinical integration. Translating data obtained from portable devices into individual risk assessments using artificial intelligence and machine learning is crucial for data analytics and digitisation. Multi-analyte sensor systems can be designed by developing systems that enable the simultaneous detection of not only Mg^{2+} but also electrolytes such as Ca^{2+} and K^{+}. Future research gaps exist in increasing healthcare accessibility in low-income areas through inexpensive, portable, and user-friendly sensor designs. In light of these perspectives, the applicability of magnesium measurement technologies not only in basic science and laboratory research but also in clinical and daily life will significantly increase. This will create new opportunities for individual health management and public health policies.

The differences in speed, sensitivity, cost and applicability of the methods used to determine magnesium were shown in tabular form and then interpreted graphically.

Table 4. Studies in the literature

Method Used	LOD/LOQ	Time	Advantages	Disadvantages	Ref.
Sequential Injection	1–5 mg/L	3 min	Fast measurement; relatively simple automation	Limited sensitivity; requires specialized equipment	(Machado et al., 2018)
EDTA titration and ISE	1.2–4.5 mg/L	-	Inexpensive; classical and well-known methods	Low sensitivity; operator-dependent; not suitable for very low Mg levels	(Aljerf & Mashlah, 2017)
µPAD	82–247 µM (62 µM)	10–90 min	Portable; low-cost; suitable for point-of-care	Longer analysis time; lower precision compared to lab-based methods	(Aguiar et al., 2022)
Coral Magnesium Kit	-	5 min (collection) + 10 min (centrifuge)	Easy-to-use; can be applied in clinical settings	Moderate sensitivity; influenced by patient habits (tobacco/alcohol)	(Singhal et al., 2023)
Colorimetry	0.02121 ± 0.00445 mg/L (working group)	Prep: 2 h, Meas: 40 min	High sensitivity; relatively low cost	Time-consuming; prone to interference; needs careful preparation	(Mohammed et al., 2024)
Commercial Kit	-	5 min	Very quick; user-friendly	May lack accuracy; variability across kits	(Silva Andrade et al., 2018)
AAS	2.57 ± 0.06 mg/L; 0.5443–0.5129 mg/L	5–80 min	High accuracy and reproducibility; widely validated	Requires laboratory, expensive instruments, trained operator	(dos Reis et al., 2020; Wijaya et al., 2021)
ICP-MS	~0.01–0.1 mg/L (very low)	Prep: 10 min, Meas: 12 min	Ultra-sensitive; multi-element detection	Very high cost; requires laboratory; complex operation	(Romano et al., 2020)
Xylidyl Blue Method	-	16 min	Relatively fast; colorimetric simplicity	Interference from other ions; limited precision	(Shekatkar et al., 2022)
Xylidyl Blue Method (variant)	-	-	Allows differentiation of health vs malignant disorders	Limited comparability; moderate sensitivity	(Aziz et al., 2018)
Spectrophotometers	-	-	Widely available; simple analysis	Low specificity; limited sensitivity	(Al-Abdaly et al., 2021)

A radar chart was created to compare methods simultaneously according to multiple criteria, such as LOD/LOQ, time, cost, and portability, and to visualise their strengths and weaknesses holistically. At this stage, data for the methods' four different parameters (LOD, time, cost, portability) were determined. Because each parameter has different units, all values were normalised to the 0-1 range. The radar chart in Figure 4 was then created.

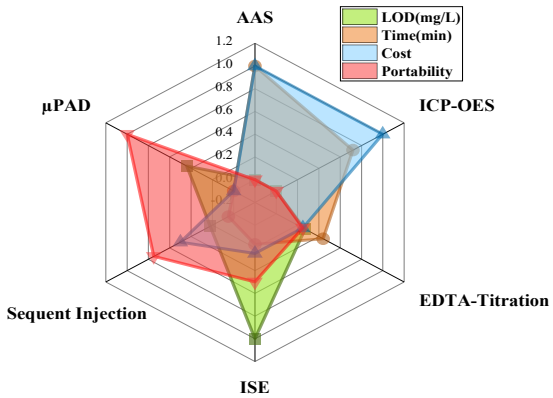

Figure 4. Multicriteria comparison of magnesium detection methods

Looking at the graph, the method with the lowest LOD value is more pointed than the others. This method offers high-sensitivity (low LOD) measurement. Methods with narrow red zones are more portable (more suitable for field applications), while those with wider red zones are laboratory-dependent. Methods closer to the centre are both faster and more cost-effective.

When the methods are evaluated, μPADs are preferred for clinical use, where speed and practicality are important. AAS or ICP-MS are preferred for research and laboratory settings where sensitivity is high. μPADs or portable ISE devices are preferred for screening and field studies, where portability and low cost are important. ICP-MS is preferred for biomarker studies. As can be seen from the graph, rather than determining a single "best" method, the criteria by which each method stands out are visually highlighted. Some methods are very sensitive (good LOD) and fast, but compromise on portability and low cost, while others are less expensive and portable, but have lower sensitivity.

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UNMANNED SURFACE VEHICLES USED FOR WATER QUALITY MONITORING

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Abstract: Water is an essential element for sustaining life, making the continuous monitoring of aquatic resources a critical task. Advances in technology have paved the way for modern systems that enable water quality monitoring with lower labor requirements and reduced operational time. Unmanned Surface Vehicles (USVs), whether remotely operated or fully autonomous, serve as mobile platforms capable of collecting data from various locations within lakes, rivers, seas, and other water bodies. Their mobility and flexibility provide significant benefits, especially in large-scale or inaccessible regions. This paper reviews USV-based water quality monitoring systems and analyzes the hardware and software components used in their development. The study focuses on microcontrollers, storage units, propulsion and navigation techniques, sensor configurations, positioning systems, and energy management strategies. Furthermore, it examines the design and functionality of control station interfaces utilized for operating USVs and visualizing real-time environmental data.

Keywords: Autonomous surface vehicles, Remote control, Water quality, Real time monitoring, Sensors.

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1. INTRODUCTION

Water is vital for life, and the survival of all living organisms on Earth depends on its state. It is used to satisfying essential needs, life quality, industrial production, and personal consumption. Most of the Earth's surface water exists seas, lakes, and rivers, which are extensively used for activities such as tourism, manufacturing, agriculture, and transportation. The quality of water, which is present in all of life, directly impact the efficiency in this area. The quality of water bodies can be evaluated through chemical, physical, and biological parameters. Standardized values help in effective decision making for sustainable water management. It is also a critical indicator in determining the cleaning, storage and maintenance of water bodies (SWQR, 2015).

Measurements in water bodies are conducted using portable sensors or by collecting samples, which are subsequently analyzed in the laboratory. However, these approaches involve significant labor and time costs. With advancements in technology, various innovative techniques have in water monitoring systems to enhance efficiency. One of method is the wireless collection of sensor data, which enables real-time monitoring and reduces the need for manual intervention. (Mukta et al., 2019). These remote monitoring methods are classified into two categories based on sensor module configurations: mobile and stationary systems. In stationary systems, one or more fixed sensor nodes are positioned on the water surface to continuously collect data from a specific location. (Duran and Yucel., 2021). In mobile systems, sensor modules can operate either on the water surface (Jo et al., 2019) or underwater (de Lima et al., 2021). Additionally, these systems can be categorized as either remotely controlled (Jo et al., 2019) or fully autonomous (Bayusari et al., 2021), depending on their operational mode. Both systems include a control and monitoring station. While sensor data in stationary systems is continuously collected from a single fixed location, mobile systems enable data acquisition from multiple points, providing a more comprehensive spatial assessment of water quality.

USVs can be defined as vessels designed to operate without a man operator. These vehicles can either be remotely controlled or function autonomously. If a USV is capable of autonomous navigation, it is referred to as an Autonomous Surface Vehicle (ASV). The usage of USVs for water quality monitoring has become increasingly widespread in recent years. A typical monitoring system consists of a USV and a control station, as showed in Figure 1 (Stateczny and Burdziakowski, 2019).

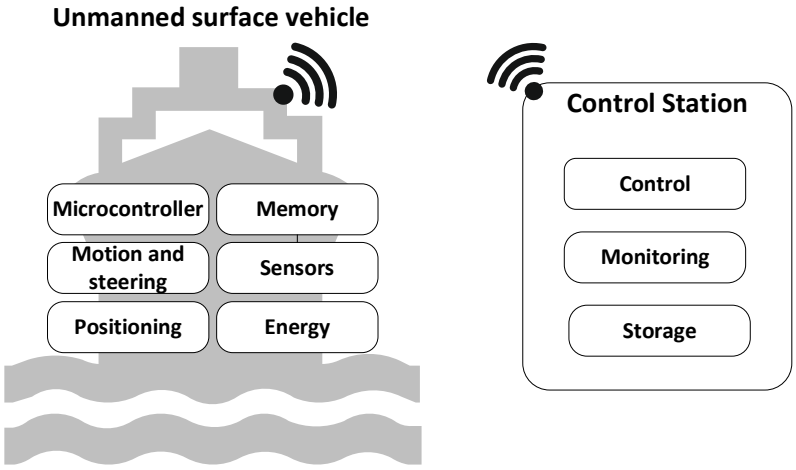


Figure 1: A typical water quality monitoring system developed using USV

1. UNMANNED SURFACE VEHICLE

USVs developed for water quality monitoring consist of including sensors, memory units, communication modules, positioning systems, motion and navigation mechanisms, power sources, and processors. This study examines USVs of varying dimensions, ranging from 50 to 150 cm in length and 30 to 100 cm in width. The research provides an overview of the system components, sensor modules, hull designs, power sources, microcontrollers, motion and navigation systems, communication modules, and control stations used in these platforms.

2.1. Sensor module

The assessment of water quality involves the evaluation of chemical, physical, and biological parameters. Sensors are utilized to detect physical and chemical properties and convert these measurements into electrical or digital signals. In USVs, sensor modules enabled the measurement of both water and atmospheric parameters. Commonly monitored parameters include pH (potential hydrogen), temperature, turbidity, oxidation-reduction potential (ORP), electrical conductivity (EC), and dissolved oxygen (DO). The functions of the modules used in water quality monitoring systems are briefly described below.

The pH value indicates the concentration of hydrogen ions in water, representing its acidity or alkalinity. pH sensors measure the balance between acidic and alkaline components in water and express it as a pH value. The World Health Organization (WHO) recommends that water should not be excessively acidic or alkaline, with an optimal pH range for drinking water typically between 6.5 and 8.5. Additionally, it is suggested that the pH value for aquatic life should remain within the range of 5 to 9 to ensure a suitable environment for biological sustainability.

Temperature is a critical parameter for aquatic ecosystems such as rivers, lakes, and seas. Variations in water temperature directly impact the quality of life for aquatic organisms, their migration ways and, in extreme cases, led to death. Temperature plays a significant role in biological activity and growth, as it affects metabolic rates and processes. Additionally, it determines the diversity of organisms that is inhabit rivers and lakes. Fish, insects, zooplankton, phytoplankton, and other aquatic species each require specific temperature ranges for survival. When temperatures exceed or fall below these optimal ranges, population sizes decline, and species may ultimately face extinction (WSS, 2018).

Turbidity is a measure of the clarity of a liquid and is an important optical property of water. It is quantified by assessing the amount of light scattered by suspended particles in a water sample when a light source is applied. The higher the intensity of scattered light, the greater the turbidity. Various materials are increased turbidity such as clay, silt, inorganic and organic matter, algae, dissolved colored organic compounds, microscopic organisms, and plankton (WSS, 2018).

The oxidative power of a solution is measured by its ORP, which also represents its self-purification capacity. Higher ORP values indicate a greater number of oxidizing agents, while lower ORP values suggest a higher concentration of reducing agents. For aquatic life, the optimal ORP range is typically between 100 mV and 200 mV. Values outside this range may indicate hazardous conditions, potentially threat the survival of aquatic organisms (Prasad et al., 2015). The ORP level of tap water is typically high, around 600 mV, due to the use of disinfectants such as chlorine. This elevated ORP value indicates strong oxidative properties, which help in eliminating harmful microorganisms and ensuring the microbiological safety of drinking water.

EC varies depending on several parameters, including temperature, pH, alkalinity, total hardness, calcium concentration, total solids, total dissolved solids, chemical oxygen demand, chloride levels, and iron concentration in water. In rivers and streams, conductivity is influenced by the geological characteristics of the surrounding area. Streams flowing through regions with granite bedrock tend to have lower conductivity, whereas those passing through clay-rich soils exhibit higher conductivity. Additionally, discharges into water bodies can alter conductivity

depending on their composition. For instance, a malfunctioning sewage system increases conductivity due to chloride, phosphate, and nitrate, while an oil spill reduces conductivity by introducing hydrophobic compounds that limit ion mobility (Bhateria and Jain 2016).

DO refers to the amount of oxygen present in water. Water bodies obtain oxygen from aquatic plants and atmospheric change. Flowing water, such as rivers and streams, typically contains higher oxygen levels compared to stagnant water bodies like ponds or lakes. Aquatic organisms need dissolved oxygen for respiration, making it a critical factor for sustaining life. Oxygen levels in water bodies can change periodically due to various environmental and biological processes. As DO directly influences aquatic ecosystems, it is considered one of the key parameters that are measured and monitored to assess water quality.

In addition to commonly used sensors for monitoring water parameters, water quality can be evaluated using sensors that measure light, color, salinity, and other related properties. These additional parameters provide valuable insights into the overall condition of aquatic environments, enabling a more comprehensive evaluation of water quality (Setiawan et al., 2022). In the developed systems, in addition to water parameters, sensors measuring temperature and humidity are also utilized to monitor atmospheric conditions. These environmental factors play a crucial role in understanding the interactions between water quality and weather conditions, providing a more comprehensive assessment of aquatic ecosystems (Xing et al., 2020). The water parameter sensors used in the sensor modules of the developed USVs are presented in Table 1.

Table 1. Sensors used on USVs to measure water parameters.

Ref.	pH	Temperature	Turbidity	ORP	EC	Chlorophyll-a	TDS	Light	Color	Salinity	DO
(Melo, et al., 2019)	X	X		X							X
(Kaizu, et al., 2011)	X	X	X		X	X					X
(Arko, et al., 2020)	X	X	X								
(Ansari, et al., 2022)	X	X	X				X				
(Shuo, et al., 2017)	X	X		X	X			X			X
(Setiawan, et al., 2022)		X						X			
(Balbuena, et al., 2017)	X	X	X		X				X		X
(Chang, et al., 2021)	X										
(Madeo, et al., 2020)	X	X		X						X	X
(Cao, et al., 2018)	X						X				
(Dsouza, et al., 2021)	X	X			X						
(Xing, et al., 2020)	X	X	X								
(Siyang and Kerdcharoen, 2016)	X	X		X	X						X

In a USV developed for water quality monitoring, the selection and quantity of sensors for the monitored parameters is determined based on the size of the USV, the scale of the study area, and the available energy capacity. This is because each additional sensor contributes to increased energy consumption and spatial constraints within the system. Fundamental sensors such as temperature, pH, turbidity, DO, and EC are commonly used to obtain a general assessment of water quality. However, the technical specifications of these sensors vary across different studies depending on the research objectives and environmental conditions.

2.2. Hull design and material

Surface vehicles are designed to remain partially submerged while ensuring they do not fully sink. To achieve this, various hull designs are utilized, including flat-bottomed boats (Fig. 2a), V-bottomed boats (Fig. 2b), round-bottomed boats (Fig. 2c), and catamarans (Fig. 2d). Each design offers distinct advantages depending on the operational environment, stability requirements, and intended application of the USV (Riley, 2021).

In addition to these standard designs, customized hull structures can be developed based on specific operational requirements. Catamaran hulls offer advantages such as stability, better water contact, reduced submersion, and increased deck space; however, they are generally not optimized for high-speed operation. Among monohull designs, V-bottom hulls provide higher speed and enhanced maneuverability, making them suitable for dynamic environments. Flat-bottom hulls good in shallow waters, allowing for efficient maneuver in narrow areas. Round-bottom hulls can design to minimize wave impact and enhancing stability in rough water conditions.

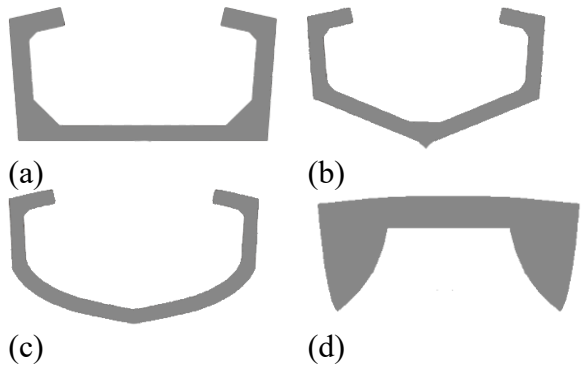


Figure 2. (a) Flat bottom, (b) V-bottom, (c) Round bottom, (d) Catamaran

Dsouza et al. (2021) developed a remotely controlled boat for monitoring water parameters. The boat is designed with a flat-bottomed hull to enhance stability on the water surface. It is reported that the square-shaped flat hull contributes to improved stability, reducing the external effects. The square hull structure is constructed using Polyvinyl Chloride (PVC) material. This is providing durability, stable buoyancy and lightweight design.

In the study by Siyang and Kerdcharoen (2016), a USV is designed in a catamaran form. The catamaran structure consisted of two V-bottomed hulls made of fiberglass, which are positioned parallel to each other. To house electronic equipment and ensure protection, a waterproof enclosure is placed in the central section between the two connected hulls. This design allowed for balanced weight distribution, with the center of gravity positioned at the midpoint, enhancing stability and structural integrity in aquatic environments. Although this design offers advantages such as enhanced stability, the alignment of the motors, propellers, and shafts positioned in both hulls are precisely adjusted to optimize their interaction with the water.

While various hull designs have been developed for surface vehicles used in water quality monitoring systems, the catamaran form is the most preferred due to its stability and spacious platform for sensor integration. Table 2 show hull types used in the literature.

Table 2. USV forms developed to measure water parameters.

Ref.	Hull Design
(Melo, et al., 2019)	Flat bottom
(Kaizu, et al., 2011)	Catamaran
(Arko, et al., 2020)	Catamaran
(Ansari, et al., 2022)	Catamaran
(Shuo, et al., 2017)	Catamaran
(Setiawan, et al., 2022)	V-bottom
(Balbuena, et al., 2017)	Catamaran
(Chang, et al., 2021)	V-bottom
(Madeo, et al., 2020)	Catamaran
(Cao, et al., 2018)	Catamaran
(Dsouza, et al., 2021)	Flat bottom
(Idris, et al., 2016)	Catamaran
(Xing, et al., 2020)	V-bottom
(Siyang and Kerdcharoen, 2016)	Catamaran

The hull material used in the development of a USV is an important factor. The material is necessary highly resistant to external environmental conditions and impermeable to water to ensure durability and long-term functionality. Additionally, it is strong enough to withstand the pressure exerted by water while the vehicle moves on the surface. Among the most used materials are iron, wood, and epoxy resin-based fiberglass composites. Epoxy resin-based fiberglass offers several advantages in terms of weight reduction, structural rigidity, ease of manufacturing, and water resistance, making it a preferred choice for USV hull construction (Mohan et al., 2016).

Different types of materials are used in the construction of USVs developed, primarily due to cost considerations. Additionally, the choice of material varies depending on the operating environment. In calm water bodies such as pools and ponds, where wave action is minimal, lighter and less rigid materials may be sufficient. However, in more dynamic environments such as lakes, rivers, and seas, where water turbulence and wave impact are higher, stronger and more durable materials are required to ensure structural integrity and long-term performance.

In a study, a plastic material is used for the hull of an USV developed for water quality monitoring. The boat is designed in the form of a flat-bottomed plastic box to increase stability. The developed USV is tested in a laboratory setting, where it is successfully floated in calm water conditions, demonstrating its buoyancy and functionality (Ansari et al., 2022). According to researchers, the system tested in calm water is not suitable for turbulent water conditions and may pose a risk, compromising the protection of electronic components.

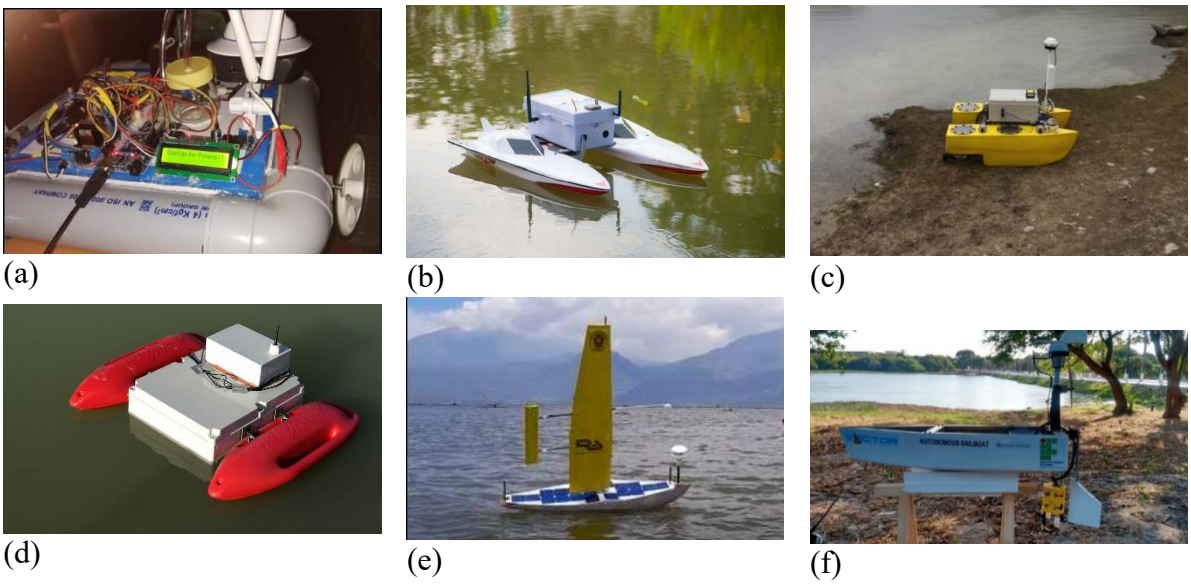
In another study, USV is designed using polyvinyl chloride (PVC) material. The V-bottom hull is constructed to house electronic components and other onboard equipment. Additionally, polystyrene extensions are attached to the edges of the hull to prevent potential capsizing. The developed USV is tested in five different lakes, demonstrating its functionality in various aquatic environments. The study suggested that the hull design can further improved and made waterproof through the integration of advanced sealing technologies and high-tech materials (Arko et al., 2020).

In the USV developed by İdris et al., a catamaran design is constructed using PVC pipes. The use of pipes in the catamaran structure allowed the USV to achieve the required speed, while the dual-hull configuration provided a spacious platform for integrating sensors and other onboard equipment. This design enhanced both stability and functional capacity, making it suitable for water quality monitoring applications (Idris et al., 2016).

The MicroUSV, an USV proposed for use in robotic research, is manufactured using polylactic acid (PLA) material via 3D printing technology. The vehicle is assembled by combining small modular components, resulting in a structure with dimensions of 230 mm in length, 89.2 mm in width, and 125.5 mm in height. Designed as a monohull, the vehicle incorporates a stabilizing at the central to enhance stability and prevent capsizing. Developed specifically for laboratory, the MicroUSV is characterized as a low-cost, rapidly produce, and easily modify platform, offering flexibility for experimental applications in water quality monitoring. (Gregory and Vardy, 2020).

In studies in large water bodies, fiberglass and plastic materials are more commonly preferred for USVs. These materials enhance the structural durability of the USV, making it safe against potential hazards encountered in open water environments. Additionally, they provide resistance to challenging terrain conditions, such as rocks, sand, and gravel. USVs developed using plastic and polystyrene materials is tested in small water bodies and pools. In these studies, the focus is primarily on electronics and software development, rather than hull design, as the controlled environment minimizes external physical challenges.

In a study conducted with a USV designed for operation in large water bodies, fiberglass material is used for the hull, and a catamaran structure is formed by connecting two separate hulls with aluminum strips. This design allowed for the placement of a waterproof casing between the hulls, ensuring the protection of electronic components. During field tests, researchers reported that the USV maintained its structural integrity despite multiple collisions with rocks near the lake shore and exposure to 5 mm diameter hailstones. These results highlight the durability and resilience of the fiberglass-based catamaran design in challenging environmental conditions (Balbuena et al., 2017). The hull designs of surface vehicles developed for water quality monitoring are shown in Figure 3.



(a) (b) (c) (d) (e) (f)

Figure 3. a) PVC material, square form (Dsouza et al., 2021), b) Fiberglass material, two v-bottom form (Siyang et al., 2016), c) Fiberglass material, catamaran form (Balbuena et al.,

2017) d) Plastic material, catamaran form (Madeo et al., 2020), e) Fiberglas material, v-bottom form (Setiawan et al., 2022), f) Fiberglass material, mono hull (Melo et al., 2019)

2.3. Power supply

In USVs developed for water quality monitoring, energy management is critical to ensuring system continuity. Power requirements are met through various sources, including wind, fuel, and electricity. Energy is primarily used to support both the navigation system and the monitoring equipment. In some studies, a shared energy source is used for both subsystems, while in others, separate power sources are used for propulsion and monitoring equipment. Batteries are commonly employed as the primary energy source for the monitoring system, as shown in Table 3.

Table 3. Energy sources used in USVs developed for water quality monitoring.

Ref.	Propulsion			System Energy	
	Electric	Gasoline	Wing	Battery	Solar Panel
(Melo, *et al.,* 2019)	X			X	
(Kaizu, *et al.,* 2011)		X		X	
(Arko, *et al.,* 2020)	X			X	
(Ansari, *et al.,* 2022)	X			X	
(Bautista, *et al.,* 2022)	X			X	
(Shuo, *et al.,* 2017)	X			X	
(Setiawan, *et al.,* 2022)			X	X	X
(Balbuena, *et al.,* 2017)	X			X	
(Chang, *et al.,* 2021)	X			X	
(Madeo, *et al.,* 2020)	X			X	
(Cao, *et al.,* 2018)	X			X	
(Dsouza, *et al.,* 2021)	X			X	
(Idris, *et al.,* 2016)	X			X	
(Xing, *et al.,* 2020)	X			X	
(Siyang and Kerdcharoen, 2016)	X			X	

In the Jetyak USV, developed for oceanographic studies, separate energy sources are utilized for the propulsion system and the monitoring system. The propulsion system is powered by a 5.2 kW gasoline engine, equipped with an 11.4 L fuel tank. This engine, weighing 135 kg, enabled the vehicle to reach a speed of 5.5 m/s. For the monitoring system, two 12 V batteries are used to supply the necessary power, ensuring the continuous operation of onboard sensors and data collection. This dual-power system enhances efficiency by optimizing fuel consumption for movement while ensuring a stable and independent power source for data collection (Kimball et al., 2014).

Energy provision in USVs is constrained by the need to maximize operational duration (autonomy) while minimizing vehicle weight and size. A commonly chosen solution involves high-capacity Lithium batteries; for example, one USV utilizes a high-capacity 12V 10000mAh Lithium battery supplemented by two separate solar panels to ensure energy maintenance during extended voyages (Tran vd. 2024).

In another system, solar and wind energy are integrated into the battery system to provide a renewable power source for the USV. The propulsion batteries are recharged using energy from renewable sources through relay-controlled charging mechanisms. The system is generated 200 Watts of electrical power from solar panels and 400 Watts from wind turbines. It provides extending operational hours and the duration the USV could remain at sea. Hybrid system also

includes a control unit to prevent overcharging, ensuring stable and efficient power management (Khaled et al., 2021).

In the ROAZ II surface vehicle, batteries are used as the primary energy source. The power supply system consists of 12 V/50 Ah LiPo battery providing power for the motors. To ensure system reliability, 12 V 3700 mAh battery packs independently power critical systems in case of failure. Additionally, an internal 12 V distribution and protection board is integrated within the hull to manage power delivery to the motors and other electronic components. The vehicle's power system is safeguarded against overvoltage and overcurrent failures (Ferreira et al., 2009). To monitor Indonesia's seawater conditions, a USV named POPTAN is developed. POPTAN utilizes wind energy to power its motors, while solar panels supply energy for system operation. This hybrid energy allowing for extended operation periods in marine environments without reliance on conventional fuel sources (Setiawan et al., 2022).

In another study, a custom-built, solar-powered USV with a catamaran design is developed to collect various water parameter data. It is stated that in the developed system, 300W of energy is produced by solar panels. This situation resulted in a maximum speed of 4 knots, which is insufficient to reach the vehicle's potential speed of 5.5 knots. Despite operating at lower speeds, the system is successfully tested over hundreds of kilometers, demonstrating its efficiency and reliability in long-duration missions (Dunbabin et al., 2009).

The boat with a 150 kg carrying capacity is developed for water sampling in a swamp environment. The boat is found two four-stroke gasoline engines, each with a maximum power output of 1.2 kW. Propulsion is provided by two 350 mm diameter fans, ensuring efficient movement through the swamp terrain. With a 5 liter fuel capacity, the boat can operate at maximum engine power for up to 6 hours. The boat is allowed for extended field operations in challenging environments (Kaizu et al., 2011).

USV propulsion and navigation systems play a critical role in determining the suitable energy source. Additionally, factors such as the size of the USV and its operational environment significantly influence energy source selection. Liquid fuel-powered USVs offer high power output, making them suitable for demanding applications. However, their environmental impact is a major disadvantage. Wind energy, which is minimal environmental impact, is a viable alternative but is limited to specific operational conditions. Batteries are among the most used energy sources in USVs today, yet their capacity remains limited compared. Increasing the number of batteries can extend operational time but also adds weight, which can negatively affect performance and maneuverability. To mitigate these limitations, renewable energy sources such as solar panels and wind turbines can be integrated into battery-powered systems. This approach enhances the sustainability and efficiency of the energy supply, ensuring longer operational durations while minimizing environmental impact.

2.4. Microcontroller

Microcontrollers are responsible for managing the entire electronic system in USVs developed for water quality monitoring. In most cases, both the water monitoring system and the USV's are controlled by a single microcontroller. However, in some studies, a separate control architecture is implemented, where one microcontroller manages the monitoring system, while another controls the USV's movement and operation. The microcontrollers used in the developed USVs are listed in Table 4.

Table 4. Microcontrollers used in USVs developed for water quality monitoring.
X: *Vehicle microcontroller,* Y: *Monitoring system microcontroller*

Ref.	Raspberry Pi	myRIO	Ardunio	STM
(Melo, et al., 2019)	X		Y	
(Arko, et al., 2020)			XY	
(Ansari, et al., 2022)			XY	
(Bautista, et al., 2022)			XY	
(Shuo, et al., 2017)		XY		
(Setiawan, et al., 2022)			Y	X
(Balbuena, et al., 2017)	X		Y	
(Chang, et al., 2021)			XY	
(Madeo, et al., 2020)			XY	
(Cao, et al., 2018)	XY			
(Dsouza, et al., 2021)			XY	
(Idris, et al., 2016)			XY	
(Xing, et al., 2020)			XY	
(Siyang and Kerdcharoen, 2016)			XY	

The capability, speed, operational efficiency, and overall performance of a USV are largely determined by the microcontroller. Since different applications have varying requirements, a single microcontroller cannot be universally applied to all USV designs. Instead, the selection of a microcontroller should be based on the specific capabilities and operational needs of the system. Several technical factors are considered in this selection process, including bit architecture (8 bit, 16 bit, or 32 bit), power efficiency, input and output interfaces, package size, RAM and ROM capacity, temperature tolerance, processor speed, and software compatibility. Choosing a microcontroller that aligns with these specifications ensures optimal system performance, reliability, and energy efficiency, enabling the USV to operate effectively in diverse environmental conditions.

In the robotic airboat "Vektor", two different microcontrollers are used to manage various subsystems. An Arduino is employed for the water parameter measurement system, while a Raspberry Pi controlled the USV's movement, navigation, and communication functions. The system utilized the Arduino Mega 1280, which is chosen for its enough I/O pins and adequate memory capacity to support sensor connections and data processing. Water parameter data collected by the Arduino is transmitted to the Raspberry Pi, which acted as the central processing unit for higher-level functions. The study specified that the Raspberry Pi B+ model is selected due to its USB interfaces, general-purpose I/O pins, Micro SD storage capability, and low power consumption, making it well-suited for efficient system operation and real-time data processing (Melo et al., 2019).

In another study, two microcontrollers are used to manage water parameter monitoring and USV navigation and control. The system incorporated two Arduino Mega 2560 microcontrollers, each assigned to a specific function. One microcontroller is responsible for surface cleaning, obstacle avoidance, and propulsion control, while the other managed position tracking and water parameter monitoring. This dual-microcontroller architecture enabled efficient task distribution, ensuring improved performance and reliability in autonomous operations. (Chang et al., 2021). In a smaller-scale USV, a single microcontroller is used to manage both the control and monitoring systems (Arko et al., 2020). This highlights the importance of microcontroller selection based on the size and functional requirements of the developed USV. The choice of a single or multiple microcontrollers directly impacts the system’s efficiency.

Although microcontrollers are widely preferred due to their lower power consumption and compact size, Kaizu et al. utilized a computer for both the USV's control system and water parameter monitoring. In their study, the computer continuously transmitted navigation and heading data to the electronic control unit, which managed the motors. Additionally, the system is designed to enable continuous data recording through a custom-developed program, allowing for real-time monitoring and long-term data storage (Kaizu et al., 2011).

In another study, the Raspberry Pi B is utilized in the development of a small-scale USV based on stereo vision. The Raspberry Pi is used to with two cameras and ultrasonic sensors for navigation and environmental perception. The system is developed on a Linux-based platform, where algorithms are executed directly on the Raspberry Pi. OpenCV is employed for image processing, while the Video4Linux2 API enabled parallel image acquisition (Neves and Matos, 2013).

2.5. Propulsion and steering

The propulsion and steering systems of a USV are responsible for navigating the vehicle to its designated coordinates. Sails and propellers are commonly used for movement, while propellers and rudders are employed for steering. In dual-propeller systems, the difference in rotation speed and direction between the two propellers acts as a rudder mechanism, enabling directional control without a separate rudder. Propellers generate thrust by use water or air, facilitating movement. The ability of propellers to generate thrust through airflow in water environments makes USVs adaptable for use in reed beds, marshes, and other challenging terrains. Additionally, the hull design of a USV directly influences the selection of propulsion and steering components. Various studies are employed different propulsion and steering systems, and Table 5 shown.

Table 5**.** Equipment used for propulsion and steering in USVs developed for water quality monitoring

Ref.	Propeller position		Steering hardware	
	Contact water	Noncontact water	Rudder	Propeller
(Melo, et al., 2019)		X		X
(Arko, et al., 2020)		X		X
(Ansari, et al., 2022)	X		X	
(Bautista, et al., 2022)	X		X	
(Shuo, et al., 2017)	X		X	
(Setiawan, et al., 2022)		X		
(Balbuena, et al., 2017)	X			X
(Chang, et al., 2021)	X			X
(Madeo, et al., 2020)	X			X
(Cao, et al., 2018)	X		-	-
(Dsouza, et al., 2021)	X		X	
(Idris, et al., 2016)	X		X	
(Xing, et al., 2020)	X		-	-
(Siyang and Kerdcharoen, 2016)	X		-	-

- *unspecified*

Motors are essential for propeller and rudder movement in USVs. While propellers require continuous movement, rudders operate effectively with intermittent adjustments. Due to these differing requirements, brushed or brushless motors are typically used for propellers, whereas servo motors are preferred for rudder control. Navigating to a target location is achieved through the precise control of the propellers and rudders. Motor operation is managed using

Electronic Speed Controllers (ESCs), which regulate motor movement based on commands received from the microcontroller. The ESC ensures speed control, enabling responsive maneuverability of the USV (Harrington and Kroninger, 2013; Kusko and Peeran, 1988; Sakama et al., 2022).

The processing core of a USV often involves a multi-tiered control architecture, where microcontrollers manage either low-level or high-level tasks to ensure efficient operation. In the case of the ROWENA prototype, the Arduino Mega 2560 was selected as the main microcontroller due to its availability and sufficient connectivity to integrate navigation sensors (GPS, compass) and a dedicated SD Card module for data storage. Conversely, more complex platforms, such as the EDSON-J USV, implement a hybrid control architecture. This design employs a main computer, running the Robot Operating System (ROS) for deliberative control and a secondary computer running a Finite State Machine (FSM) for hierarchical control (executing low-level tasks such as navigation algorithms and propeller control). The Jetson TX2 was chosen for its flexibility, native Linux/Python compatibility, computational power (NVIDIA Pascal GPU), and energy efficiency (Mendoza-Chok vd. 2022).

In USVs which used dual-propeller systems, the difference in rotation speed and direction between the two motors is used to control the vehicle's heading. In contrast, rudder-based systems determine the direction of movement based on the angular position of the rudder relative to the hull. The distance, direction, and angular difference between the current position and the target location are calculated by the microcontroller. Based on these calculations, appropriate commands are sent to the motors and steering system, ensuring that the USV adjusts its trajectory and moves toward the target (Wang et al., 2009).

In single-propeller USVs, a rudder is essential for changing the vehicle’s direction. A stern-mounted rudder helps maintain a minimal angular offset between the USV’s heading and the target direction. However, rudders are less effective for large directional changes and have several limitations, including speed reduction and the need for a larger turning radius. As a result, rudders are typically more suitable for larger, slower-moving vessels that do not require rapid maneuvers. In some USVs, propeller-based steering systems are used instead of rudders. Propeller-driven control improves the maneuverability of the vehicle, allowing for faster and sharper turns. This makes propeller-based systems ideal for sensitive and rapid maneuvers, enabling the USV to navigate efficiently in complex environments where agility is required.

2.6. Communication

Communication between the USV and the control station is established wirelessly, enabling real-time data exchange and remote operation. However, there is no universal connectivity solution that suits all physical environments and operating conditions. Various wireless communication protocols are employed depending on the range, data transmission requirements, and environmental factors. Commonly used standards include Wi-Fi, ZigBee, Bluetooth, LoRa, and GSM, each offering different advantages in terms of range, power consumption, and data transfer speed. Table 6 shows the communication technologies used in USV systems.

Wi-Fi is a widely used, low-cost communication solution with an outdoor range of up to 100 meters. It operates using IEEE 802.11x radio technologies, which transmit and receive wireless data over the 2.4 GHz and 5 GHz frequency bands. Bluetooth is a short-range, low-power, and cost-effective digital radio communication technology. Depending on the power class, its range

typically varies between 1 to 10 meters. While Bluetooth requires significantly less power than Wi-Fi, its coverage area and data transmission rates are also much lower. Bluetooth transceivers operate in the 2.4 GHz frequency band with a 1 MHz bandwidth per channel. ZigBee is a wireless personal area network technology based on IEEE 802.15.4, capable of communicating over distances of up to 2500 meters. It offers advantages such as low cost, low power consumption, and extended coverage, making it suitable for long-range, energy-efficient applications in USV communication systems (Singh et al., 2014).

In the ECOSAIL system, ZigBee is used for communication between the control station and the USV. Sensor data collected from the USV is transmitted to the control station via ZigBee at 10 second intervals. The ZigBee modules are configured to operate on similar frequency channels for efficient data transfer. The study highlights that ZigBee, instead of LoRa, is chosen due to its mesh networking capability and high-speed data transmission, which enable real-time monitoring and reliable communication between the USV and the control station (Ang et al., 2022).

In another study, the water quality monitoring system and the main control unit on the USV are designed as separate components, with communication between them established via Wi-Fi. Sensor data collected from the monitoring system is first recorded and then transmitted to the main control unit over Wi-Fi. Subsequently, the data is sent to a cloud-based control station using GPRS. The transmission to the control station is carried out in JSON format, where the data is parsed and stored in the cloud for further analysis and monitoring (Cao et al., 2020).

GSM technology enables remote data communication by utilizing cellular network infrastructure. The communication range depends on the coverage area provided by the service provider. Various GSM-based communication technologies include General Packet Radio Service (GPRS), Universal Mobile Telecommunications System (UMTS), and Long-Term Evolution (LTE), each offering different data transfer speeds and capacities. These technologies provide varying levels of performance, presenting distinct advantages and disadvantages depending on the application requirements. When compared to other wireless communication methods, GSM-based systems are more costly due to service provider fees. However, their global coverage makes them a solution for applications requiring data transmission over large geographical areas. Despite this advantage, GSM infrastructure dependency can vary based on local service provider policies and network investments, potentially affecting availability and performance in certain regions. The selection of a communication standard is entirely dependent on the specific communication requirements and the scope of the application. Factors such as range, data transfer speed, power consumption, environmental conditions, and infrastructure availability are considered to determine the most suitable wireless communication technology for a given USV system.

Tablo 6. Communication methods used in USVs developed for water quality monitoring.

Ref.	Wi-Fi	ZigBee	Lora	GSM	Bluetooth	3DR Radio
(Melo, et al., 2019)	X					
(Arko, et al., 2020)	X					
(Ansari, et al., 2022)	X			X	X	
(Bautista, et al., 2022)				X		
(Shuo, et al., 2017)		X				
(Setiawan, et al., 2022)			X			X
(Balbuena, et al., 2017)	X					
(Chang, et al., 2021)					X	
(Madeo, et al., 2020)		X				
(Cao, et al., 2018)				X		
(Dsouza, et al., 2021)					X	
(Idris, et al., 2016)						X
(Xing, et al., 2020)	X					
(Siyang and Kerdcharoen, 2016)		X				X

In a study, LoRa and 3D Radio Telemetry Module are compared for communication performance. The evaluation is conducted by transmitting 20 data packets, and parameters such as transmission distance, data quality, and power consumption are analyzed. The results indicated that the 3DR Radio Telemetry Module is efficient up to 300 meters, whereas the LoRa module maintained effective communication up to 10,500 meters. Additionally, LoRa exhibited lower power consumption in idle mode, but during data transmission, its power consumption is observed to be nearly twice as high as that of the 3D Radio Telemetry Module (Setiawan et al., 2022).

2. CONTROL STATION

The control station is responsible for operating the USV, monitoring incoming data, and storing collected information. USV control can be categorized into two main approaches: manual remote operation and autonomous navigation. In remotely operated USVs, the vehicle is controlled manually by commands sent from the control station, allowing the user to navigate forward, backward, left, or right. The thrust system's speed and direction, as well as the rudder angle, are adjusted according to the received instructions, enabling precise movement control. For USVs, coordinate data can be transmitted either in real-time from the control station or predefined before deployment. The system calculates the optimal route between the current position and the target destination, adjusting motor speed and rudder movements accordingly. During navigation, external environmental factors such as wind and waves are considered. To handle these challenges, various path-planning algorithms can be implemented, including linear, nonlinear, adaptive, and intelligent routing methods, depending on the complexity of the operational environment.

A study discusses the use of various methods for developing a route control system in an USV. Several control strategies, including Proportional-Integral-Derivative (PID) control, optimal control, adaptive control, intelligent control, robust control, and sliding mode control, have been evaluated for their suitability in USV navigation. Due to environmental disturbances such as wind, waves, and currents, fuzzy logic control has been proposed as an alternative approach for handling uncertain and nonlinear dynamics in complex systems. This method enhances the USV's ability to adapt to unpredictable conditions, making it particularly useful for real-world applications where precise modeling of environmental influences is challenging (Azzeri et al., 2015).

In a study conducted using a USV developed for water quality monitoring, a grid-based path-planning method is implemented. Water parameter values are measured at grid points spaced 10 meters and 40 meters apart. The USV completed its journey across 45 points with 10 meters spacing in 20 minutes, while the journey across 130 points with 40-meter spacing took 144 minutes, requiring an additional battery to sustain operation. The collected data is transmitted to the control station, where it is processed and utilized for mapping purposes using the ArcGIS software (Kaizu et al., 2011).

In a study conducted by Cao et al., a mobile application is developed as a control station for USV operations. The application is designed to integrate mapping, remote control, and data query functionalities, enabling real-time monitoring of the USV's position directly from the mobile interface. The system allowed for instant task assignment, enabling the USV to navigate dynamically based on operational needs. Upon reaching the target coordinates, the USV measured water parameter values and transmitted the data to a server for further analysis. The study concluded that the system is suitable for real-world experimental applications, demonstrating its potential for practical deployment in field operations (Cao et al., 2018).

The control station is used for both monitoring and controlling the USV. Data visualization plays a crucial role in understanding and analyzing collected information, making the system more effective for users. A well-designed control station should be user-friendly, support multiple platforms, and provide real-time tracking of the USV on a map. Additionally, the control station should feature an interface for manual remote control, allowing for immediate intervention when necessary. To ensure uninterrupted operation, the connection between the control station and the USV always remains stable. A comparison of the devices and software used in various control stations, including whether they support remote manual control and how target coordinate data is uploaded, is presented in Table 7. Additionally, the different control units implemented with various devices and software are illustrated in Figure 4.

Table 7. Control station features in USVs developed for water quality monitoring

Ref.	**Target Coordinate Information**	**Manual Remote Direction**	**Monitoring Device/Software**
(Melo, et al., 2019)	Saved at first	No	PC / Google Maps
(Kaizu, et al., 2011)	Saved at first	No	-/-
(Arko, et al., 2020)	Saved at first	Yes	-/-
(Ansari, et al., 2022)	-	No	PC / -
(Bautista, et al., 2022)	Saved at first	No	-/-
(Shuo, et al., 2017)	Send instantly	Yes	PC / Lab View
(Chang, et al., 2021)	Saved at first	Yes	PC / Lab View
(Madeo, et al., 2020)	-	Yes	-/-
(Cao, et al., 2018)	Send instantly	No	Smart Phone / Mobile App
(Dsouza, et al., 2021)	-	Yes	Smart Phone /-
(Idris, et al., 2016)	Send instantly	Yes	PC /-
(Siyang and Kerdcharoen, 2016)	-	Yes	PC / Smart Phone

- *unspecified*

(a) (b) (c) (d)

Figure 4. (a) Control unit developed using LabVIEW (Chang et al., 2021), (b) Control unit developed with a mobile application (Cao et al., 2018), (c) Mobile application with text-based command input (Dsouza et al., 2021), (d) Computer-based control unit (Kaizu et al., 2011)

3. CONCLUSIONS

This study demonstrates the potential of USV-based systems for effective water quality monitoring through the integration of multiple sensors and wireless communication technologies. The catamaran hull design, with its modular and detachable structure, ensures stability, increased payload capacity, and ease of transport, making the system adaptable for diverse operational scenarios. By reducing cost, time, and labor requirements, while simultaneously enhancing safety, USVs represent a practical and scalable solution for environmental monitoring. The findings highlight that flexible communication alternatives, such as Wi-Fi, 4G/5G, and LoRa, can be tailored to different mission requirements, improving system reliability and independence. Moreover, the use of portable control stations and custom-developed software strengthens operational flexibility. In conclusion, USV-based monitoring systems offer a promising approach to real-time water quality assessment. Future studies should focus on long-term field validation, integration of additional water quality and biological sensors, and the development of advanced autonomous navigation and data-processing algorithms to further improve system performance and applicability.

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N/A

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Conflict of Interest
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