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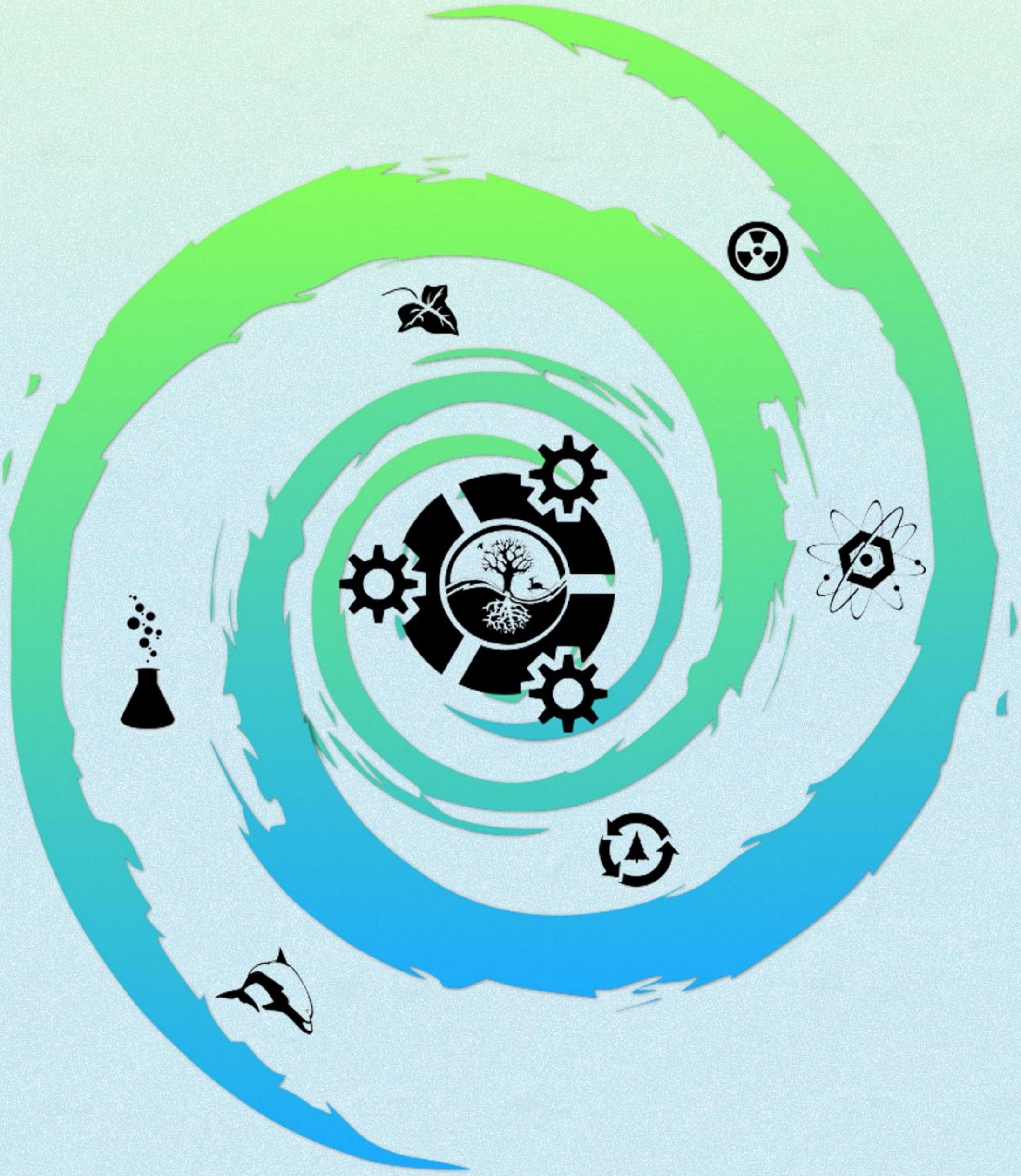

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Impact of Zeta Potential on Copper Adsorption of Surface-Modified Hydroxyapatites Derived From Fish Bone Waste

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ABSTRACT

Zeta potential emerges as a crucial parameter in understanding particle surface charges and assessing the stability of colloidal systems. It also serves as a key indicator in determining electrostatic interactions between surfaces and ions. In this study, hydroxyapatite (HA) derived from fish waste was functionalized with histidine (HA_4) and 4-Aminohippuric acid (HA_5), and their surface properties and heavy metal ion (Cu^{2+}) adsorption capacities were investigated. Zeta potential measurements performed after surface modification showed that both modifications induced a negative charge on the surface. The surface modified with histidine exhibited a zeta potential in the range of -3.48 to -5.09 mV, while the surface modified with 4-Aminohippuric acid demonstrated a higher negative charge. Adsorption experiments revealed that HA5 exhibited a superior Cu^{2+} binding capacity of 9.96 mg/g compared to HA_4 (9.52 mg/g). The findings indicate that zeta potential and the presence of functional groups on the surface play a significant role in the retention of heavy metal ions. These results suggest that modified fish bone surfaces can serve as effective and sustainable adsorbents for environmental applications.

INTRODUCTION

Today, increasing industrial production, urbanization, and changing consumption habits result in the generation of large amounts of organic and inorganic waste. The uncontrolled release of these wastes into the environment leads to soil, water, and air pollution. In addition, it poses serious threats to ecosystem balance and human health. Therefore, it is of great importance not only to dispose of these wastes but also to utilize them as secondary raw materials in order to achieve sustainable environmental management (Özkara & Akyıl, 2019; Siddiqua et al., 2022; Hajam et al., 2023; Kurama, 2023; Mishra et al., 2023; Ghulam & Abushammala, 2023; Dehkordi et al., 2024). In recent years, within the framework of the circular economy approach, the reprocessing of waste into high value-added materials has both reduced environmental burden and provided economic benefits. In particular, numerous studies have focused on converting agricultural, animal, and industrial wastes into usable forms for applications such as biosorbents, composites, catalysts, construction materials, and biomedical uses (Wang et al., 2023; Mujtaba et al., 2023; Gherman et al., 2023). Waste materials such as fish bones, shells, and skins obtained from the fish processing industry can be converted into biomaterials like hydroxyapatite (HA) due to their high calcium phosphate content. Hydroxyapatite is a widely used material, especially in fields such as heavy metal adsorption, tissue engineering, and drug delivery systems (Duta et al., 2021; Mondal et al., 2023). Therefore, transforming wastes like fish bones into functional and usable materials through appropriate surface modifications offers environmentally friendly and economically sustainable solutions. Zeta potential is an electrokinetic parameter that describes the electric charge on the surface of a particle and its interaction with the surrounding liquid medium. This potential is a crucial indicator that directly influences the stability of particles in suspension, surface reactivity, and adsorption mechanisms (Danaei et al., 2018; Serrano-Lotina et al., 2023). Zeta potential plays a significant role, especially in the retention of metal ions and organic pollutants on solid surfaces. Adsorption capacity largely depends on the electrostatic attraction forces between the surface and the target ions or molecules. If the surface zeta potential is negative, it facilitates the approach and retention of positively charged metal ions on the surface. Conversely, if the surface is positively charged, it can support the adsorption of negatively charged ions. Therefore, the magnitude and sign of the zeta potential play a fundamental role in determining the binding tendency of ionic pollutants to the surface (Xu et al., 2003; Anielak & Grzegorczuk-Nowacka; 2011; Marzun et al., 2014). The zeta potential value can also vary depending on factors such as the nature of the functional groups on the surface, surface modifications, and the pH of the environment. Therefore, by controlled modification of the surface, adjusting the zeta potential to a desired range can enable selective and efficient adsorption of target pollutants. In this context, characterization of zeta potential is regarded as a fundamental evaluation criterion in the development of high-performance adsorbent materials (Serrano-Lotina et al., 2023; Martins et al., 2025; Khani et al., 2025). Heavy metal pollution, particularly the release of copper (Cu^{2+}) ions into the environment through industrial waste, poses a serious threat to human health and ecosystems. High concentrations of copper cause toxic effects leading to liver damage, neurological disorders, and disruption of environmental balance. The high costs and inefficiencies of traditional treatment methods necessitate the development of low-cost, environmentally friendly, and high-capacity alternative adsorbents. In this context, hydroxyapatite (HA) derived from biological sources is a promising material for heavy metal removal. Hydroxyapatite obtained from fish bones possesses a natural ion exchange capacity due to its calcium phosphate structure and provides effective adsorption, especially through the substitution of Ca^{2+} ions with other metal ions such as Cu^{2+} (Kizilkaya et al., 2010). In this study, the surface of hydroxyapatite derived from fish bones was modified with histidine (HA_4) and 4-Aminohippuric acid (HA_5), and their copper adsorption capacities and zeta potential properties were comparatively investigated. The effects of these modifications on both surface charge (zeta potential) and copper binding mechanisms were examined in detail.

MATERIAL AND METHODS

Functionalization of Bone Surfaces With Organic Acids

In this study, the surface modification of fish bone particles with Histidine (HA_4) and 4-Aminohippuric acid (HA_5) was performed according to our previous work (Tan et al., 2014; Kızılkaya et al., 2015). Briefly, 2.5 g of hydroxyapatite obtained from fish bones was placed in a 50 mL reaction vessel containing 25 mL of acetonitrile solution with 0.1 M histidine (or 4-Aminohippuric acid). An inert gas (e.g., nitrogen) was continuously purged into the reaction medium, and the system was refluxed at boiling temperature under a condenser for 8 hours. After completion of the reaction, the mixture was cooled and left to stand for 12 hours, followed by washing five times with technical water, methanol, and acetonitrile consecutively by centrifugation at 2000 rpm. The obtained modified solid phase was dried in an oven at 45°C and prepared for subsequent analyses.

Determination of Zeta Potentials

The zeta potentials of the modified products were measured using a Malvern Nano-ZS device at the Central Research Laboratory of Bilecik Şeyh Edebali University. Distilled water was used as the dispersant solvent during the measurements. The analysis was conducted under the following conditions: temperature at 25°C, Zeta Run set to 12, measurement position at 2 mm, dispersant refractive index of 1.330, viscosity of 0.8872 cP, and dispersant dielectric constant of 78.5. Approximately 1 mg of the sample was suspended in 10 mL of water, introduced into the measurement cell, and then analyzed.

Copper Removal and Adsorption

Within this scope, the copper removal performance of the obtained materials was investigated. $CuCl_2 \cdot 2H_2O$ (Merck, 1.02733.0250) was used to prepare a solution with a concentration of 50 mg/L. Each material was subjected to adsorption at an adsorbent-to-solution ratio of 1:200 for 30 hours. After adsorption, the liquid phase was filtered through a 0.45 μm syringe filter and analyzed by flame atomic absorption spectroscopy (AAS-Flame) to determine the amount of adsorbed copper, completing the experiment. For copper analysis, a Photron halogen cathode lamp (HGD0599, Australia) was used. Calibration for copper analysis was performed using a Merck multi-element standard solution IV (111355). The copper measurements were conducted at the Faculty of Marine Sciences and Technology, Çanakkale Onsekiz Mart University, using a Shimadzu AA-6300 Atomic Absorption Spectrophotometer with flame (AAS-Flame). Acetylene and dry air were used as fuel gases during the AAS-Flame measurements.

RESULTS AND DISCUSSION

Surface modification is an effective method to enhance the chemical and electrostatic properties of adsorbent materials, thereby increasing their selectivity and binding capacity toward target pollutants (Petrovic et al., 2022). Histidine contains both an imidazole ring and amino and carboxyl groups in its structure. This configuration particularly enhances its potential to form coordinative bonds with metal ions. During modification, histidine typically binds to the surface via its carboxyl group, while the imidazole and amino groups remain free, contributing to adsorption capacity (Holeček, 2020). It generally attaches to the surface through its carboxyl group, while the amino groups can form chelate bonds with positively charged metal ions, thereby increasing the surface adsorption efficiency. Both molecules alter the charge balance on the hydroxyapatite surface, playing a decisive role in the zeta potential, and thus have the capacity to create effective adsorbent surfaces where electrostatic attraction and complexation mechanisms work synergistically. The main objective of this study is to elucidate the mechanisms underlying the changes in copper adsorption capacity following the modification of hydroxyapatite derived from fish bones with organic acids. Within this scope, surface charge characterization was performed through zeta potential measurements, adsorption experiments were conducted to determine capacities, and the performances of both modifications were compared. The obtained results are expected to contribute to the development of next-generation adsorbents for wastewater treatment and biomedical applications. Zeta potential, also known as electrokinetic potential, refers to the effective electric charge present on the surface of particles in colloidal dispersions. This value determines the repulsive or attractive forces between particles, providing insight into their dispersion and stability states. Measurement of zeta potential is an important technique for understanding, controlling, and characterizing the surface charge of colloidal and aggregate systems (Serrano-Lotina et al., 2023). Charges on the particle surface attract oppositely charged ions from the surrounding medium, forming a double-layer interface. The potential measured within the slipping plane of this structure is called the zeta potential. A high zeta potential prevents particles from aggregating, thereby increasing the stability of colloidal suspensions. Typically, systems with zeta potential values between 0 and ±5 mV tend to rapidly coagulate, ±10 to ±30 mV indicate instability, ±30 to ±40 mV moderate stability, ±40 to ±60 mV good stability, and values above ±60 mV are considered to have excellent stability (Pochapski et al., 2021; Rodriguez-Loya et al., 2023).

Figure 1 presents the zeta potential distribution spectra of HA_4 and HA_5. The zeta potential distribution obtained after modification of fish bones with histidine reveals significant changes in surface chemistry. Considering that the modification with histidine occurs via acidic groups and that histidine molecules bind to the surface through these groups, it is understood that the other amino and nitrogen groups present in histidine remain free. This structure considerably influences the chemical and functional properties of the surface. Due to the imidazole ring in histidine, it can carry both positive and neutral charges depending on the pH. However, the obtained data indicate that the surface generally acquires a negative charge. This phenomenon may arise from the acidic groups in the histidine structure or the calcium phosphate compounds naturally present on the modified bone surface. Additionally, covalent bonding or electrostatic interactions between histidine and the surface could explain this negative charge balance. However, zeta potential measurements indicate that the surface is strongly negatively charged. This suggests that the free basic groups are insufficient to alter the overall surface charge, and that naturally occurring negatively charged species such as phosphate groups in the bone matrix dominate the system. Consequently, histidine modification creates a surface structure that both maintains a negative charge balance and introduces functional groups, thereby enhancing the material interaction with biological systems and its multifunctional potential. The negative surface charge plays a supportive role in colloidal stability by increasing electrostatic repulsion forces between particles. These findings indicate that histidine-modified fish bones are promising candidates for drug delivery systems, tissue engineering, or other biomaterial applications. While the negative surface charge reduces aggregation tendency and improves stability, the biologically compatible nature of histidine may also support cellular interactions. However, since a high negative charge can differently affect protein adsorption and cellular responses, careful evaluation according to the application field is necessary. In this context, investigating surface charge behavior under varying pH and ionic strength conditions is important for better understanding the system performance in biological environments.

The zeta potential distribution measured after modification of fish bones with 4-Aminohippuric acid (HA_5) indicates significant changes in surface chemistry and colloidal stability. The negative zeta potential values likely arise from the carboxyl groups of 4-Aminohippuric acid and the phosphate groups naturally present in the bone matrix. These groups, especially under physiological or mildly basic pH conditions, become deprotonated and carry negative charges. The negative surface charge enhances electrostatic repulsion forces between particles, thereby strengthening the colloidal stability of the suspension and reducing particle aggregation. Chemically, 4-Aminohippuric acid is a molecule containing both carboxyl and amino functional groups. The charge state of these groups varies depending on the environmental pH. The carboxyl group deprotonates in basic environments to form negatively charged carboxylates, while the amino group protonates in acidic conditions, gaining a positive charge. Therefore, the zeta potential of the surface is highly sensitive to pH changes, and the charge profile of the modified surface may vary accordingly. This surface characteristic offers certain advantages and considerations for practical applications. While the negative surface charge positively influences colloidal stability, positively charged regions can enhance interactions with biological systems. Since cell membranes are negatively charged, positive surface groups may support cell adhesion. Consequently, the fish bone surface modified with 4-Aminohippuric acid acquires a complex structure carrying both negative and positive charges, significantly affecting both the physical stability and biological interaction potential of the surface. Therefore, this type of surface structure can be evaluated for versatile biomedical applications.

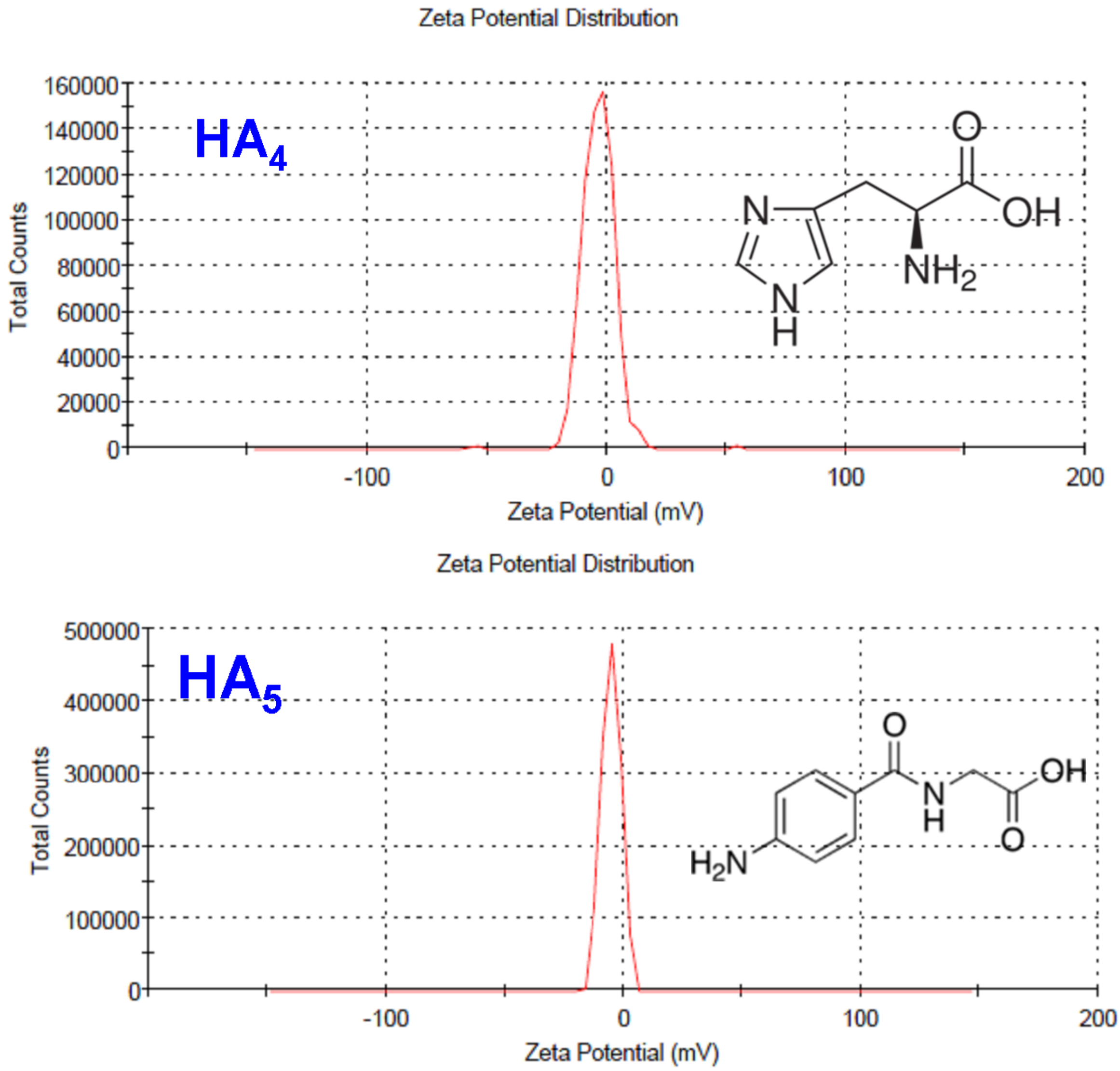


Figure 1. Spectrum of zeta potential distribution of HA_4 and HA_5

Figure 2 presents the zeta potential and surface conductivity results of HA_4 and HA_5. The zeta potential values measured after modification of the hydroxyapatite (HA) surface with histidine (HA_4) and 4-Aminohippuric acid (HA_5) reveal significant differences in surface chemistry and stability. Both modifications induced negative zeta potentials on the surface, indicating the presence of acidic groups and electrostatic repulsion between particles. In the histidine modification, zeta potential values ranged approximately from –3.48 mV to –5.09 mV. Despite histidine being an amino acid that can carry positive or neutral charges depending on pH, these low negative values indicate that the modified surface is generally negatively charged. This effect may result from the interaction of histidine carboxyl group with calcium ions in hydroxyapatite and the dominant influence of phosphate groups on the bone surface. The low negative zeta potential suggests partial neutralization of the surface charge by the modification, leading to moderate colloidal stability. Conversely, the 4-Aminohippuric acid modification generated higher negative zeta potential values on the surface. This can be explained by the presence of both carboxyl and amino groups in 4-Aminohippuric acid and the strong ionic bonding of carboxylate groups with the hydroxyapatite surface. It can be inferred that the 4-Aminohippuric acid modification imparts more negative charge groups on the surface, thereby providing higher colloidal stability compared to histidine. Overall, while histidine modification produces a low and limited negative charge, 4-Aminohippuric acid modification leads to a more pronounced increase in negative charge, contributing to a more stable colloidal system. These differences affect the potential use of the modified surfaces in biomedical applications. In particular, the high negative charge from 4-Aminohippuric acid modification can reduce particle aggregation and improve efficiency in drug delivery systems. Meanwhile, histidine modification, with its lower negative charge, may offer advantages for cell adhesion in certain biological environments. In conclusion, 4-Aminohippuric acid provides a more effective modification of the hydroxyapatite surface than histidine by increasing surface charge and enhancing colloidal stability.

In the adsorption studies, the amount of adsorption is expressed as q_e, which represents the amount of adsorbate adsorbed per gram (g) of adsorbent, calculated in milligrams per gram (mg/g). The adsorption capacity in the experimental studies was calculated using the following equation (1) (Kizilkaya & Tekinay, 2011):

$$q_e = \frac{V \times (Co - Ce)}{W} \times 1000 \quad (1)$$

In this formula;

q_e: The amount of substance adsorbed per unit adsorbent (mg/g)

V: The volume of the solution (mL)

Co: Initial adsorbate concentration of the solution (mg/L)

Ce: The concentration of adsorbate remaining in the solution after adsorption (mg/L)

W: Adsorbent amount (g)

At the end of the adsorption study, the percentage of the adsorbed substance removed from the solution relative to the initial concentration of the solution was calculated for each material and expressed as R% (percent removal). The percent removal (R%) for each material was calculated using the following equation (2):

$$R(\%) = \frac{(Co - Ce)}{Ce} \times 100 \quad (2)$$

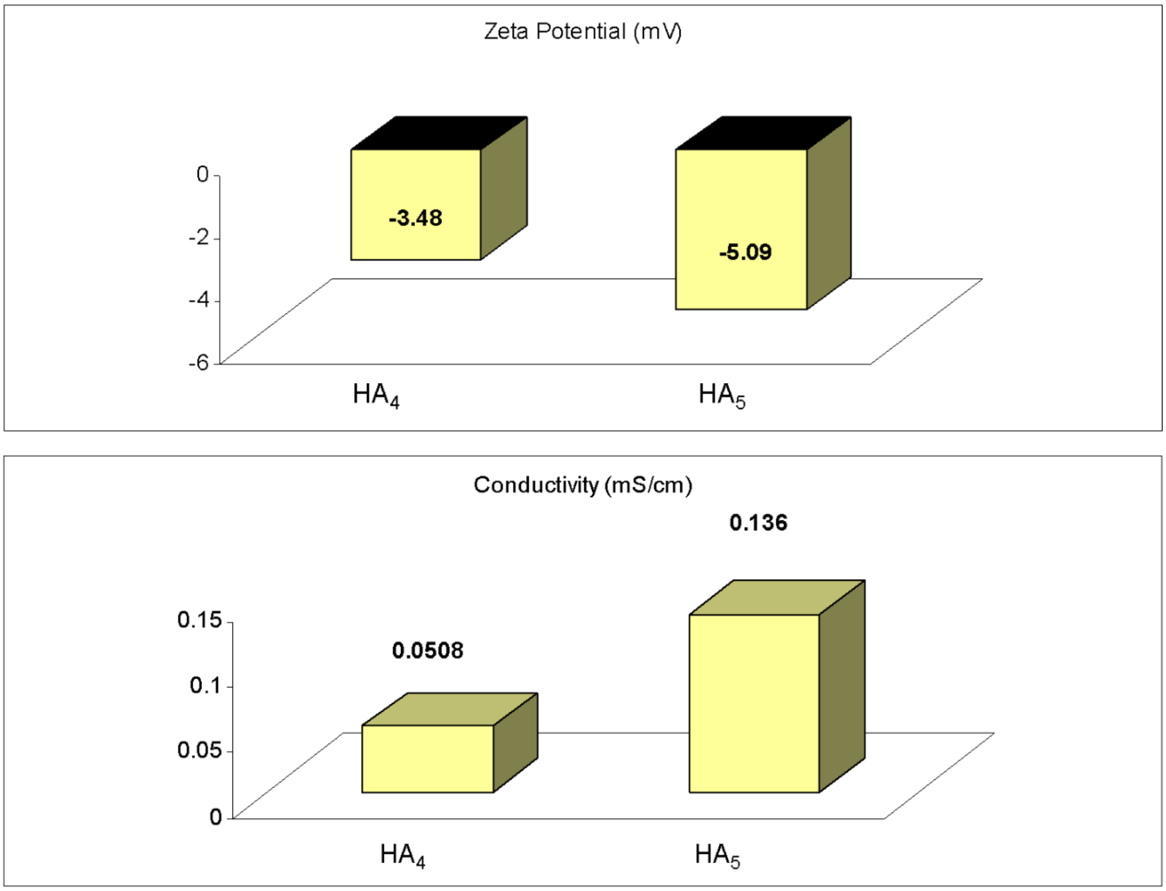
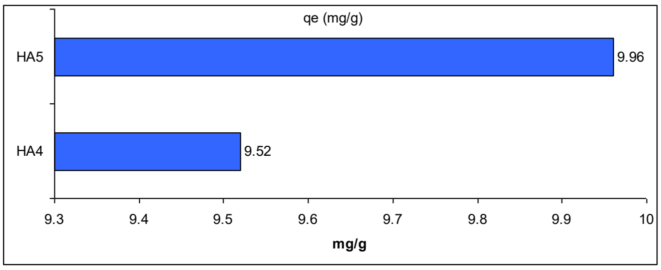


Figure 2. Representation of the zeta potential and surface conductivities of HA_4 and HA_5

The hydroxyapatite structure of fish bones is highly effective in binding heavy metals such as copper (Cu^{2+}). This binding primarily occurs through two mechanisms as ion exchange and chelation. Initially, calcium ions (Ca^{2+}) in the hydroxyapatite structure can be replaced by copper ions. In this process, Cu^{2+} ions substitute for Ca^{2+} ions in the crystal lattice and become incorporated into the structure. This natural ion exchange property plays a significant role in heavy metal retention by fish bones. However, in this study, the copper-binding effect was investigated through surface modification of hydroxyapatite with histidine (HA_4) and 4-Aminohippuric acid (HA_5). Notably, the HA_5 modification exhibited higher performance with an adsorption capacity of 9.96 mg/g compared to HA_4 as 9.52 mg/g (Figure 3). The HA_5-modified surface also exhibited a more negative zeta potential value, which can facilitate stronger electrostatic attraction of positively charged copper ions to the surface. Additionally, the larger molecular structure of HA_5 may create more binding sites on the surface, enhancing copper adsorption capacity. In conclusion, the natural ion exchange capability of hydroxyapatite can be influenced by organic modifications to improve copper binding capacity. Particularly, fish bones modified with 4-Aminohippuric acid can serve as effective adsorbent materials for removing heavy metals like copper from wastewater. Such biomaterials offer a cost-effective and environmentally friendly option for environmental remediation applications.

The effect of histidine-modified fish bone surface on the adsorption of Cu^{2+} ions is closely related to the chemical changes occurring on the surface. The adsorption behavior exhibited by this modification toward Cu^{2+} ions is determined by both the zeta potential values and the presence of free amino and imidazole groups in the histidine molecule. The negative surface charge obtained from the zeta potential measurements indicates that the surface can generate electrostatic attraction forces with positively charged ions, particularly transition metal cations such as Cu^{2+}. This electrostatic attraction facilitates the migration of Cu^{2+} ions toward the modified surface, enabling initial contact. However, adsorption is not limited to electrostatic interactions alone; chemical bonding also plays a significant role. At this point, the structural features of the histidine molecule come into play. During modification, histidine typically binds to the surface via its carboxyl group, leaving the amino group and imidazole ring free on the surface. These groups, particularly, possess the capacity to form coordinative bonds with Cu^{2+} ions. The nitrogen atoms in the imidazole ring and the free amino group can form strong complexes with Cu^{2+} ions. Due to the high coordination tendency of Cu^{2+} ions, they readily bind with such ligands, facilitating the formation of stable complexes. In this context, histidine modification imparts a dual-mechanism adsorption system to the surface, enabling the retention of Cu^{2+} ions through both electrostatic attraction and chemical complexation. This results in high affinity of the surface toward Cu^{2+} ions and enhances adsorption efficiency. Moreover, this structure offers a functional alternative for environmental remediation applications aimed at removing toxic heavy metal ions like Cu^{2+} from water. In conclusion, the negative zeta potential of the histidine-modified fish bone surface allows the attraction of Cu^{2+} ions to the surface, while the free amino and imidazole groups chemically bind these ions, providing stronger and more durable adsorption. This dual interaction improves the effectiveness of the surface in heavy metal removal and highlights such modifications as environmentally friendly and sustainable solutions.



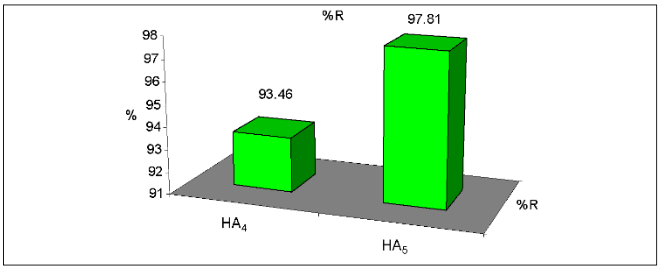


Figure 3. Results of copper adsorption of HA_4 and HA_5

The zeta potential of approximately –5.09 mV for the fish bone surface modified with 4-Aminohippuric acid (HA_5) allows for important inferences regarding the adsorption of Cu^{2+} ions. This slightly negative value indicates that the surface potential to generate electrostatic attraction with positively charged Cu^{2+} ions is limited. Generally, higher negative zeta potential values facilitate stronger electrostatic binding of metal cations to the surface, whereas a charge around –5 mV corresponds to a moderate level of electrostatic interaction. However, the structure of 4-Aminohippuric acid provides a basis for an adsorption process that is not limited to electrostatic interactions alone. While the mildly negative zeta potential supports some degree of Cu^{2+} ion attraction, the primary adsorption mechanism is dominated by the chemical binding capacity of functional groups. As a transition metal, Cu^{2+} ions exhibit a strong tendency to complex with ligands and can form stable chemical bonds with functional groups present on the HA_5-modified surface. This mechanism enables effective adsorption even when electrostatic attraction is weak. Consequently, the –5.09 mV zeta potential value indicates that Cu^{2+} ions bind to the surface not only electrostatically but also through chemical complexation. The 4-Aminohippuric acid modification offers a multifunctional binding environment by presenting diverse functional groups on the surface, resulting in an effective, sustainable, and environmentally friendly adsorbent system for the removal of cationic heavy metals such as Cu^{2+} from aqueous solutions.

CONCLUSION

In this study, the changes in zeta potential and copper (Cu^{2+}) adsorption capacities of hydroxyapatite (HA) surfaces derived from fish bones, modified with histidine (HA_4) and 4-Aminohippuric acid (HA_5), were comparatively evaluated. The analyses revealed that both modifications induced negative zeta potentials on the HA surfaces. The zeta potential of the histidine-modified surface ranged between –3.48 mV and –5.09 mV, indicating a moderate level of negative surface charge. In contrast, the surface modified with 4-Aminohippuric acid exhibited significantly more negative zeta potential values, suggesting a stronger electrostatic attraction capacity. Examination of copper adsorption data showed that the HA_5 modification demonstrated superior performance with an adsorption capacity of 9.96 mg/g compared to 9.52 mg/g for the HA_4 modification. This finding indicates that the higher negative charge generated by HA_5 facilitates the attraction of positively charged Cu^{2+} ions to the surface, thereby enhancing adsorption capacity. Additionally, it is suggested that the carboxyl and amino groups present in 4-Aminohippuric acid synergistically support ion binding. In the case of histidine modification, the presence of imidazole rings and amino groups contributed to some degree of Cu^{2+} ion binding; however, the relatively lower zeta potential limited the overall adsorption capacity. In conclusion, this study demonstrates how functional molecule modifications of fish bone-derived hydroxyapatite surfaces affect their adsorption capabilities toward heavy metal ions. Notably, the 4-Aminohippuric acid modification, with its higher negative surface charge, forms a more effective adsorbent for Cu^{2+} removal, while histidine modification provides a lower but still significant adsorption capacity due to its limited surface charge. These findings suggest that modified fish bone surfaces hold promise for sustainable and environmentally friendly remediation applications.

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Compliance with Ethical Standards

Conflict of Interest

The author declares that there is no conflict of interest.

Ethical Approval

For this type of study, formal consent is not required.

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Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

AI Disclosure

Generative AI (e.g., ChatGPT 4.0, DeepSeek) was used for grammatical review of the introduction and discussion sections. The author validated all outputs and assume full responsibility for the content.

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Interdisciplinary Trends in the Studies of *Diadema setosum*: A Bibliometric Analysis of the Period 1980-2025

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ABSTRACT

This study presents the first comprehensive bibliometric analysis of research conducted between 1980 and 2025 on the invasive long-spined sea urchin *Diadema setosum*. Using VOSviewer, 213 publications retrieved from the Web of Science Core Collection (TS= "*Diadema setosum*") were analyzed to assess publication trends, disciplinary scope, collaboration networks, citation impact, co-citation patterns and thematic clusters. The results reveal that the species is rapidly spreading in the Mediterranean and that there has been a sharp increase in publications since 2014, coinciding with a decline in 2022-2023 that corresponds to reported mass mortality events. The co-citation analysis consists of three intellectual clusters encompassing research on (i) marine ecology and echinoid phylogeography, (ii) invasion biology and Mediterranean monitoring, and (iii) disease ecology and mortality events. While marine and freshwater biology dominate the disciplinary profile, emerging environmental themes include ecotoxicology, microplastic exposure, pathogenic interactions, and biomaterial applications (e.g., chitin, chitosan, collagen), with low Total Link Strength (TLS) indicating limited integration. Japan, the USA and China are identified as the leading countries in research. Türkiye is placed within the top 10 in publication numbers but its citation visibility is reported as low because international collaboration is limited. An overall increase in publications has been observed after 2010 and studies related to the expansion of the species into the Mediterranean have contributed to this trend. Our findings indicate that research on *D. setosum* has traditionally been based on classical marine ecology and invasion frameworks, but is increasingly expanding into molecular ecology, disease dynamics and biotechnological applications. Supporting the sustainable use of the *D. setosum* species requires strengthening interdisciplinary approaches, encouraging multi-center collaborations, integrating open genomic and ecological data, understanding invasive dynamics, and assessing ecological risks.

INTRODUCTION

Diadema setosum (Leske, 1778) is an opportunistic detritivore/omnivore that plays an important role in controlling benthic algae cover as an ecologically dominant herbivorous species in reef ecosystems (Vafidis et al., 2021). Beyond its natural range in the Indo-Pacific and Red Sea, it was first recorded in Türkiye's Kaş Bay in 2006, thus entering the Mediterranean as an invasive species (Yokes & Galil, 2006). Increased sea water temperatures in recent years have accelerated the spread of *D. setosum*, with a sudden and rapid increase observed after 2018 (El-Sayed et al., 2020; Vafidis et al., 2021; Dimitriadis et al., 2023; Gökoğlu et al., 2023). This situation clearly demonstrates the effects of climate change-related marine biogeographic shifts on the distribution of living organisms. However, sudden and widespread deaths reported in the Aegean and Levant basins between 2022 and 2023 have resulted in the loss of more than 90% of sea urchin populations (Zirler et al., 2023a; Skouradakis et al., 2024). Clinical symptoms included spine shedding, mucosal integrity breaches and tissue necrosis and molecular analyses reported that these deaths were associated with *Vibrio* spp. bacteria (Zirler et al., 2023a; Dinçtürk et al., 2024; Skouradakis et al., 2024; Roth et al., 2024).

Although it has no economic or commercial importance in our country, it has been reported that *D. setosum* may pose a threat to public health, especially in tourist areas, due to the risk of physical contact caused by its spines (Zirler et al., 2023a). In addition, it has been reported that its abrasive effects on the substrate and the changes it causes in the habitat structure may negatively affect ecosystem services, particularly coastal-based economic activities such as diving tourism (Uthicke et al., 2009). Therefore, interdisciplinary research is of great importance for a comprehensive understanding of the ecological, economic and public health impacts of species such as *D. setosum*.

The quantitative and structural mapping of scientific research has become even more important, especially with the rapid increase in productivity over the past half-century. The paradigm shift described by Price as the "transition from small science to big science" has made it necessary to measure and track information due to the increase in the number of publications, citations, and researchers (Price, 1963; Bornmann & Mutz, 2015). This momentum has become even more apparent with the expansion of large databases, the spread of the open access movement and the proliferation of interdisciplinary collaborations (Larivière et al., 2015; Piwowar et al., 2018).

In this process, bibliometric analyses have become not only a tool that provides rough performance metrics, but also an analytical framework that analyzes the intellectual structure, evolution, collaboration networks, and information flow of scientific fields (Aria & Cuccurullo, 2017; Donthu et al., 2021). In addition to classic indicators such as impact factor, total citation count, and h-index, network-based approaches such as co-authorship, co-citation, bibliographic matching and keyword co-occurrence are also used. Software such as VOSviewer (van Eck & Waltman, 2010), CiteSpace (Chen, 2006), and bibliometrix/Biblioshiny (Aria & Cuccurullo, 2017) provide decision-makers with powerful tools for visualizing the structural-topological characteristics of scientific fields.

Today, bibliometric analyses have become a widespread and effective method for analyzing the historical development, thematic orientations and scientific priorities of fields such as fisheries and marine biology. Aksnes & Browman (2016) evaluated publication trends in marine research over a 30-year period and showed that despite an increase in scientific output, interdisciplinary collaboration remained limited. Despite its spread as an invasive species in the Mediterranean, the scientific literature on *D. setosum* has been limited to heavy metal, distribution and descriptive ecological records (Grignard et al., 1996; Minn et al., 2004; Yokes & Galil, 2006; Nader & Indary, 2011; Cheang et al., 2015; Bronstein et al., 2016, 2017; Al Najjar et al., 2018; Şimşek et al., 2018; Nour et al., 2022; Uğurlu & Duysak, 2022; Gökoğlu et al., 2023; Vimono et al., 2023; Uğurlu, 2023). Bibliometric analyses show that studies on this species are quite limited both geographically and thematically; they focus on topics such as biomaterial potential, toxicological properties, biopolymer production and eco-physiological adaptation and do not adequately represent the species (Bronstein et al., 2017).

These gaps in the literature have begun to be gradually filled in recent years with increasing interdisciplinary approaches. Uğurlu et al. (2023a) conducted morphological and mineralogical analyses of the crystal structures in *D. setosum* testa, revealing the potential of these materials for low-loss microwave devices. The same researchers produced chitosan and chitin from the spines and shells and suggested that the biomaterials they obtained be evaluated as environmentally friendly biopolymers (Uğurlu & Duysak, 2023). Different studies have found that different heavy metals accumulate in the tissues of this species, suggesting that *D. setosum* could be used as a potential bioindicator (Al Najjar et al., 2018; Uğurlu, 2023). Additionally, the collagen biomaterial isolated from the species was identified as Type 1 collagen (Uğurlu et al., 2023b).

Such studies reposition *D. setosum* not only as an invasive organism but also as a model marine organism for biotechnological, environmental and toxicological research. However, despite all these contributions, the fact that these studies are not sufficiently visible in international bibliometric databases highlights the need to increase the integration of Türkiye-based scientific production into global knowledge networks.

D. setosum is an invasive sea urchin species that was transported to the Mediterranean via the Lessepsian passage. It has become the focus of multidisciplinary research due to its dominant grazer effect on benthic ecosystems, biomaterial potential and toxicological significance. However, despite this growing interest, a systematic evaluation of the temporal, geographical and thematic characteristics of scientific publications on this species has not yet been conducted.

The main objective of this study is to present a comprehensive bibliometric analysis of the *D. setosum* literature using a dataset comprising a total of 213 academic studies published worldwide between 1980 and 2025, obtained from the Web of Science Core Collection (WoS) database using the search string "TS=*Diadema setosum*." The analysis includes publication trends by year, journals in which they were published, author and institutional productivity, country-based collaboration structures, keyword clusters, most cited publications and intellectual knowledge networks. In these analyses, both quantitative and visual-based information mapping was created using VOSviewer open-source bibliometric software. The objectives and outputs of this study can be summarized as follows:

- For the first time, a scientific productivity and collaboration analysis focusing solely on the *D. setosum* species and based on the Web of Science database has been conducted.
- It reveals the bibliometric counterparts of ecological, biomaterial, biopolymer and toxicological research themes in the literature related to the species.
- It evaluates the position of Türkiye-based publications within the global literature, their citation visibility and their position in international collaboration networks.
- It strategically identifies research gaps, emerging thematic clusters and future research potentials.
- In addition, this study aims to systematically reveal the global research trends and multidisciplinary dimensions of *D. setosum* using bibliometric methods, thereby providing a data-based foundation for the formulation of scientific policies related to the species.

MATERIAL AND METHODS

In this study, bibliometric data were obtained from the Web of Science (WoS) Core Collection database, which is interdisciplinary and highly reliable among scientific publications. The data set was obtained from the WoS platform due to its comprehensive search capabilities, widespread use for bibliometric analyses and high reliability. Data access was performed on July 26, 2025. The search was conducted using the query string "TS=*Diadema setosum*" and records matching all searchable fields, including title, abstract, author keywords and Keywords Plus®, were included in the search. The publication date range was 1980-2025, and no date restrictions were applied. All document types were included to ensure a comprehensive evaluation of the literature. The search included the following WoS indexes:

- Science Citation Index Expanded (SCI-Expanded)
- Emerging Sources Citation Index (ESCI)
- Conference Proceedings Citation Index-Science (CPCI-S)
- Book Citation Index-Science (BKCI-S)
- Zoological Record (ZR)

After filtering, a total of 213 records were evaluated. The data set was exported in .txt format to include complete bibliographic metadata and citation information. Bibliometric mapping and network visualization were performed using VOSviewer software (version 1.6.19). The basic parameters used in the network analysis were as follows: i) a minimum of two documents were required for a co-author to be included in the co-authorship analysis and ii) a minimum of two occurrences were required for keyword matches. No manual editing, correction, or classification was performed, and all analyses were conducted using the original data obtained from the WoS platform.

A co-citation analysis was used to identify influential studies that shape the conceptual framework of this field. This method maps publications that are frequently cited together, revealing the intellectual foundations of the research field. The bibliometric indicator Total Link Strength (TLS) was used to measure the cumulative strength of co-citation links for each reference in the network. Additionally, the number of citations for each reference was recorded based on the analyzed dataset (WoS Core Collection, 1980–2025).

RESULTS

Number of Publications by Year

When examining the distribution of scientific publications related to *D. setosum* by year, it can be seen that a very limited number of studies were produced between 1980 and 2010. During this period, the annual number of publications generally ranged from 1 to 4 and mostly exhibited a scattered production profile. However, a notable increase was observed in the period after 2011. In particular, the number of publications reached 9 in 2014 and 2015 and this increase became more pronounced in 2016, reaching 18 publications. It has been determined that 13 publications were produced in 2020, 10 in 2022, 15 in 2023 and 18 again in 2024. The fact that 7 publications have been recorded as of 2025 (up to the date of data collection) indicates that the number may increase further by the end of the year. These data reveal that scientific interest in the species has gained momentum over the past decade and has become more visible on the research agenda. The increase is thought to be related to multidimensional research topics such as the species' invasive spread in the Mediterranean, its environmental impacts and its biotechnological potential.

A significant increase in publications has been observed since 2010, with notable peaks in 2014 and 2024. These peaks are thought to be related to increased interest in the species' spread in the Mediterranean and ecological concerns reported during this period. In contrast, the decline observed in 2022 can be interpreted as a temporary shift of resources and scientific interest to other scientific fields following the Covid-19 pandemic.

Types of Publications

When scientific publications on *D. setosum* are classified by type, it is determined that the highest number is peer-reviewed "Article" (n=190). This is followed by publications of the "Proceedings Paper" type consisting of reports (n=13) and "Review Article" (n=3) (Figure 2). Additionally, the literature includes 2 Meeting Abstract and Short Note, 1 Editorial Material, 1 Correction and 1 Book Chapter (Figure 2). This distribution shows that the research topic has been examined largely through original research articles, but is also represented in a small number of publications of different types.

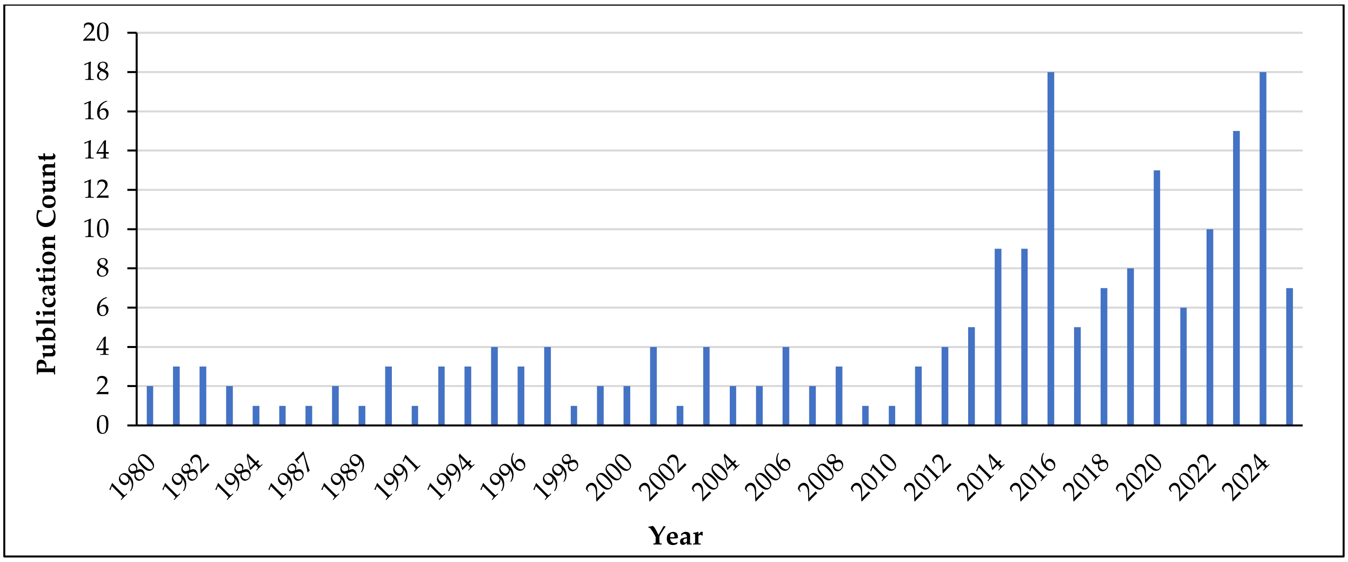

Figure 1. Distribution of publications on *Diadema setosum* retrieved from the Web of Science Core Collection (1980-2025). The trend line illustrates temporal shifts in research intensity, highlighting post-2018 acceleration associated with invasive expansion and mass mortality events (2022-2023). Data extracted using the query string "TS=*Diadema setosum*" (n=213).

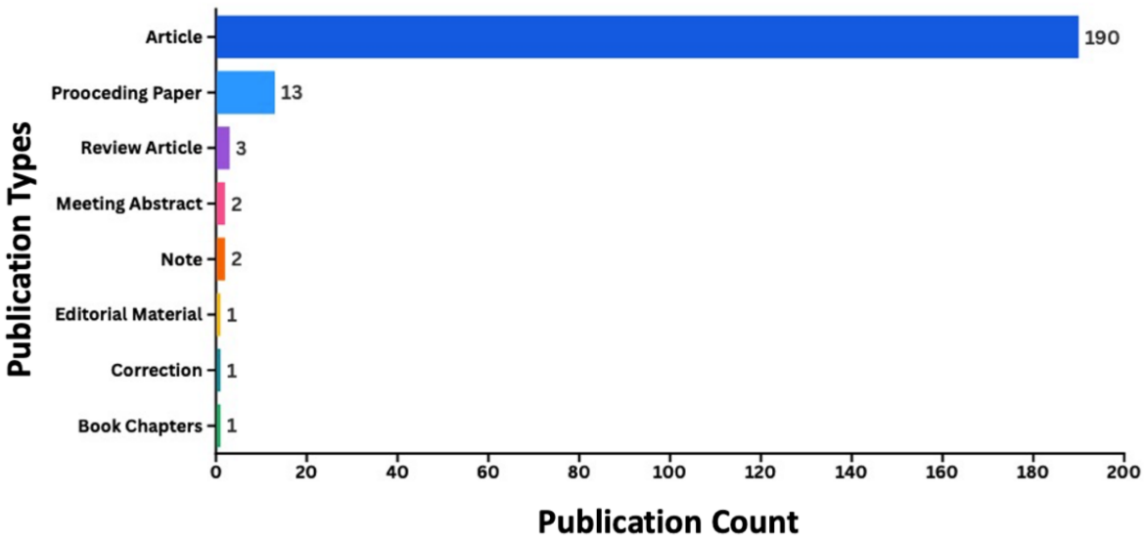

Figure 2. Distribution of publication types on *Diadema setosum* (n=213). Categories include all article types as indexed in Web of Science.

WoS Categories

When examining the distribution of scientific publications on *D. setosum* according to Web of Science (WoS) categories, it was determined that the majority of studies were concentrated in the Marine & Freshwater Biology (n=95) category. This category represents the main area of focus for research in terms of the species' basic ecological context. This is followed by the categories Oceanography (n=33), Ecology (n=34), Zoology (n=30), Fisheries (n=22) and Environmental Sciences (n=22). These categories indicate that the studies address the distribution of the species in marine ecosystems, its ecological role and its environmental impacts.

In addition, a significant number of publications have been produced in fields such as Biochemistry & Molecular Biology (n=11), Biology (n=9), Geosciences Multidisciplinary and Multidisciplinary Sciences (each n=8). In fields such as Biodiversity Conservation, Food Science & Technology, and Toxicology (n=7), Chemistry, Medicinal, and Pharmacology & Pharmacy (n=6) and Reproductive Biology (n=5), a focus on more specific biological and applied topics has been observed (Figure 3).

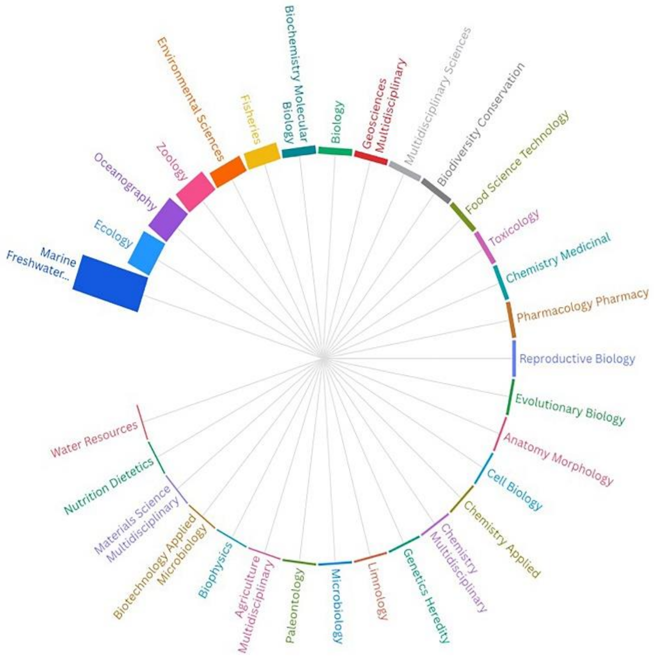

Figure 3. Distribution of *Diadema setosum* publications across the top 31 Web of Science categories. Categories were determined using WoS metadata tags, illustrating the dominance of "Marine & Freshwater Biology" and related ecological disciplines, while emerging representation in toxicology, biomaterials and molecular biology suggests interdisciplinary expansion.

Although they have a lower number of publications, research has also been found in categories such as Limnology, Anatomy & Morphology, Cell Biology, Applied Chemistry, Genetics & Heredity, Microbiology, and Paleontology (each with n=3). In addition, a wide variety of subfields with only one or two publications, such as Biophysics, Materials Science Multidisciplinary, Biotechnology Applied Microbiology, Materials Science Multidisciplinary, Nutrition Dietetics, Water Resources, demonstrate that *D. setosum* is also present in different scientific topics (Figure 3).

This broad disciplinary range shows that the species is not only of ecological interest but also of scientific interest in terms of its biochemical, toxicological, biotechnological and even engineering-based aspects, and that it is approached from a multidisciplinary perspective.

Institutions and Countries with the Highest Number of Publications

When publications on *D. setosum* were examined on an institutional basis, it was determined that Tel Aviv University (n=16) made the most significant contribution. This institution is followed by the Hellenic Centre for Marine Research (n=11), the Russian Academy of Sciences (n=10), Hong Kong Baptist University (n=9), the Smithsonian Institution, University of Putra Malaysia and the University of Hong Kong (each with n=7) (Figure 4). The higher education institutions that have published the most from Türkiye are Ege University, İskenderun Technical University, Muğla Sıtkı Koçman University and Akdeniz University (each with n=4-5) (Figure 4). This distribution shows that *D. setosum* research is being conducted by different research networks located in both Europe and Asia within a multi-centered structure.

In the country-level assessment, Japan was found to have made the most scientific contributions with 40 publications. Japan was followed by the United States (n=27), the People's Republic of China (n=18), Greece, Indonesia and Israel (each with n=17). The number of publications originating from Türkiye is 15, which places Türkiye in the top 10. In terms of literature contributions related to the species, the contributions of France and Italy (n=14), Malaysia (n=12), Russia (n=11) and the United Kingdom (n=10) are also noteworthy. These literature distributions and numbers indicate that *D. setosum* has become a subject of research both in its natural distribution areas and in regions where it is invasive and that it exhibits a wide geographical distribution in the international literature.

Although Türkiye-based institutions publish a high number of articles, their international visibility remains low due to the fact that most research is published in local journals and international collaborations are limited. This situation shows that researchers in Türkiye need to publish their work in journals with higher impact factors and strengthen international collaborations.

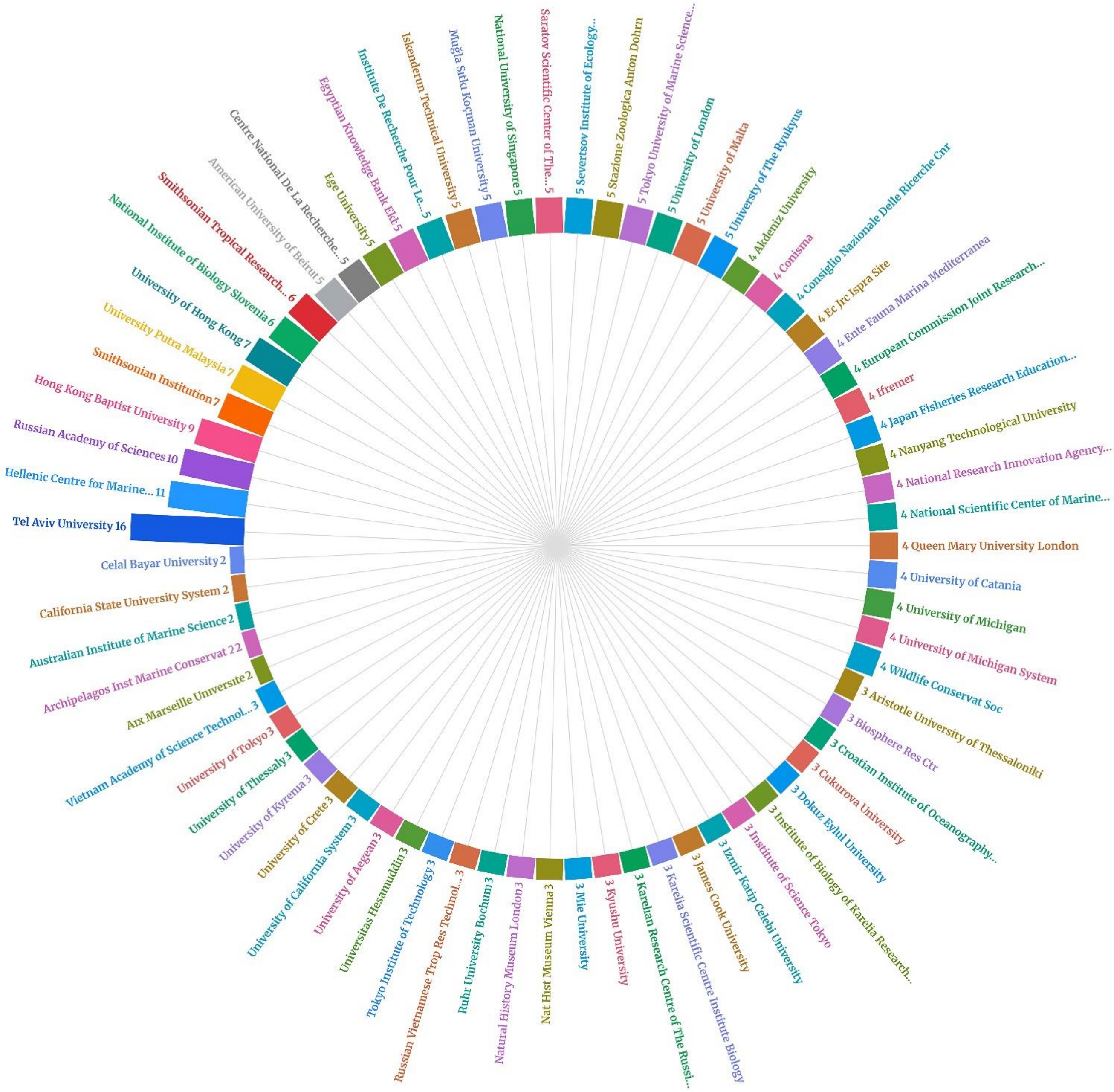

Figure 4. Leading institutional contributors to *Diadema setosum* research (n=213). Node size corresponds to the number of publications per institution and color intensity reflects co-authorship link strength as visualized.

Publication Titles

When examining the journals in which scientific studies on *D. setosum* have been published, it was determined that the highest number of studies were published in the *Journal of Experimental Marine Biology and Ecology* (n=10). This journal is followed by *Marine Biology* and *Mediterranean Marine Science* (n=8 each). Six studies were published in *Marine Pollution Bulletin* and *Zoological Science*, while five studies were published in *Coral Reefs* and *Thalassas* (Figure 5).

Among the journals hosting four scientific studies, *Invertebrate Reproduction Development* and *Marine Ecology Progress Series* stand out; while *Comparative Biochemistry and Physiology B*, *Invertebrate Biology*, *IOP Conference Series: Earth and Environmental Science*, *Journal of Environmental Biology*, *Marine Ecology Progress Series* and *Regional Studies in Marine Science* each feature three studies (Figure 5).

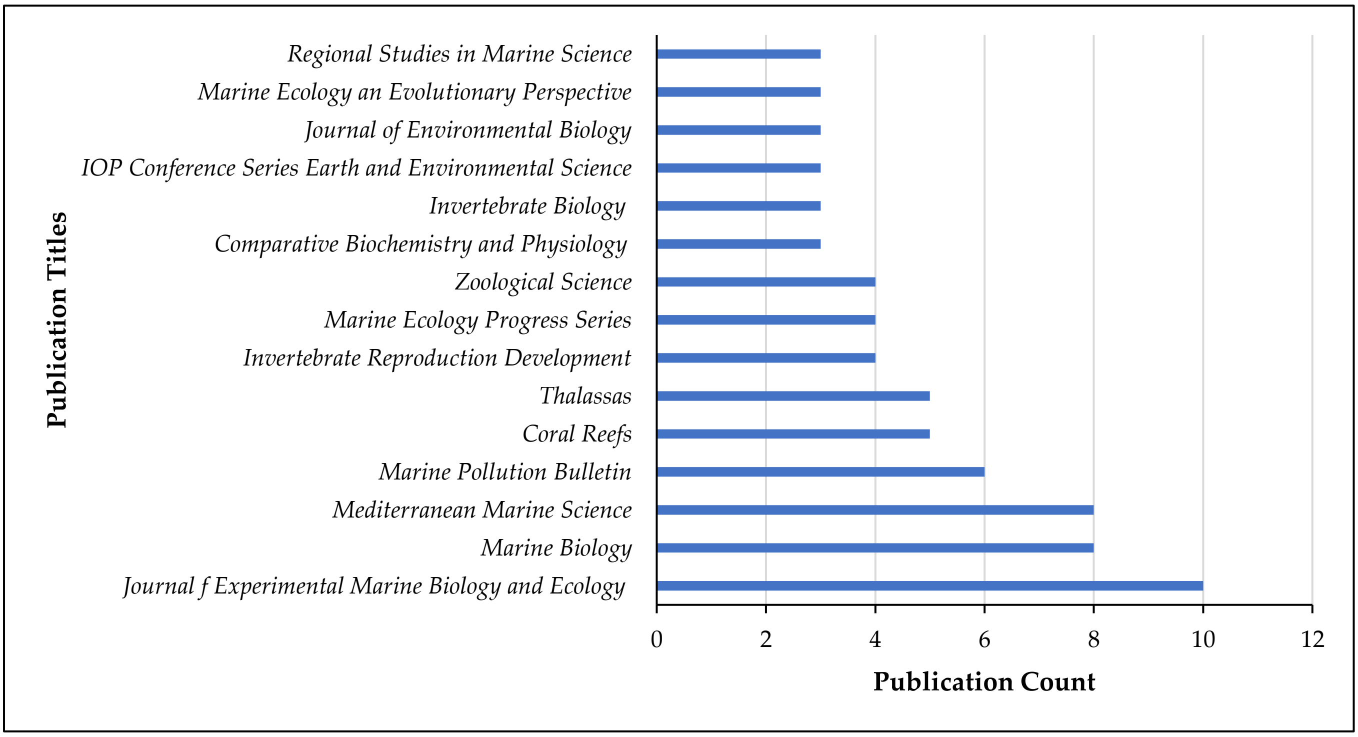

Figure 5. Main journals (top 15) publishing *Diadema setosum* research. The selection of journals is based on publication frequency in WoS-indexed records and shows the concentration in marine biology publications (e.g., *Journal of Experimental Marine Biology and Ecology*, *Marine Biology*) and the gradual inclusion of multidisciplinary outlets.

In the remaining numerous journals, only one or two scientific studies were found. This distribution shows that research outputs on *D. setosum* are concentrated in a specific core group of marine and environmental biology journals, but due to the multidisciplinary nature of the subject, it is addressed in a wide range of publications. The diversity of journals highlights that the subject is addressed in various scientific fields such as ecology, toxicology, physiology, marine sciences and biochemistry.

Most Prolific Authors

When scientific publications on *D. setosum* are examined by author, Omri, B. (Israel) and Jian-Wen, Q. (Hong Kong) (each with 8 publications) are among the most prolific scientists. These researchers are followed by Yusoff, M. F., (Malaysia) Crocetta, F. (Italy) and Arshad, A. (Malaysia) with 7 publications. These researchers are followed by Gerovasileiou, V. (Greece), Motokawa, T. (Japan) and Abd Rahman, M. A. (Malaysia) with 6 publications each. In addition, it has been determined that authors such as Coppard, S. E. (London), Tiralongo Francesco (Italy), Loya, Y. (Israel), Yapıcı, S. (Türkiye), Corsini-Foka, M. (Greece), Campbell, A. (London) and McClanahan, T. (Kenya) have contributed to the subject with 5 studies each. Among researchers based in Türkiye, Uğurlu, E. stands out in the international literature with four publications. Overall, this distribution shows that *D. setosum* research is being conducted by different research groups at both the geographical and interdisciplinary levels.

Citation Network of Publications

When examining the citation network for publications related to *D. setosum*, it is seen that Jian-Wen, Q. has the highest number of citations. The researcher’s four studies have received a total of 116 citations. Lau, D. C. C., who received 88 citations for his two studies and Bronstein, O. who received 44 citations for his three studies, follow him. Kurashima, A., and Ishikawa, T. each received 30 citations for their three studies, while Kroh, A., received 27 citations for his two studies. Researchers such as Kurogi, H. (26), Kaneko, K. (21), Matsumoto, H. (21) and Osako, K., (21) have also received more than 20 citations (Figure 6).

Among the authors who received a more limited but still significant number of citations, Zirler, R., and Corsini-Foka, M., stand out with 22 citations from two publications. Among the researchers who made significant contributions to the local literature, Uğurlu, E.'s three publications received 10 citations, while Duysak, Ö.'s two publications received a total of 8 citations. The works of researchers named Alan, V. (7) and Öndeş, F. (7) have also found their place in the literature. This citation distribution shows that certain authors have created a high impact in a short period of time and that this field has taken shape around certain researchers from a bibliometric perspective (Figure 6).

Co-Citation Network: Intellectual Foundations of *D. setosum* Research

A co-citation analysis was conducted to identify the intellectual roots and fundamental literature supporting *D. setosum* research. The analysis revealed a network dominated by classical ecological and invasion biology studies, as well as molecular and biogeographic research and highlighted a shift from descriptive ecological studies toward integrative and multidisciplinary approaches (Figure 7).

Fundamental Studies in Marine Ecology and Evolutionary Biology

Lessios et al. (2001) (*Evolution*, 15 citations; TLS=240) emerged as the most influential reference, forming the intellectual basis for phylogeographic frameworks for echinoderms and studies of population structure in *D. setosum*. Pearse (1970) and Pawson (1983) provided early ecological perspectives on echinoderm distribution and reproductive biology that are frequently cited together in a historical context.

Invasion Biology and Mediterranean Expansion

Yokes & Galil (2006) (*Aquatic Invasions*, 13 citations; TLS=237) and Bronstein et al. (2017) (*Marine Ecology Progress Series*, 7 citations; TLS=159) are central nodes linking invasion biology to the species' Mediterranean colonization.

Mass Mortalities and Recent Ecological Changes

Recent co-citation clusters bring together studies documenting mass mortality events, such as Zirler et al. (2023a) and Skouradakis et al. (2024), demonstrating a shift in research focus from studies on the distribution of the *D. setosum* species to ecosystem disturbance and disease ecology.

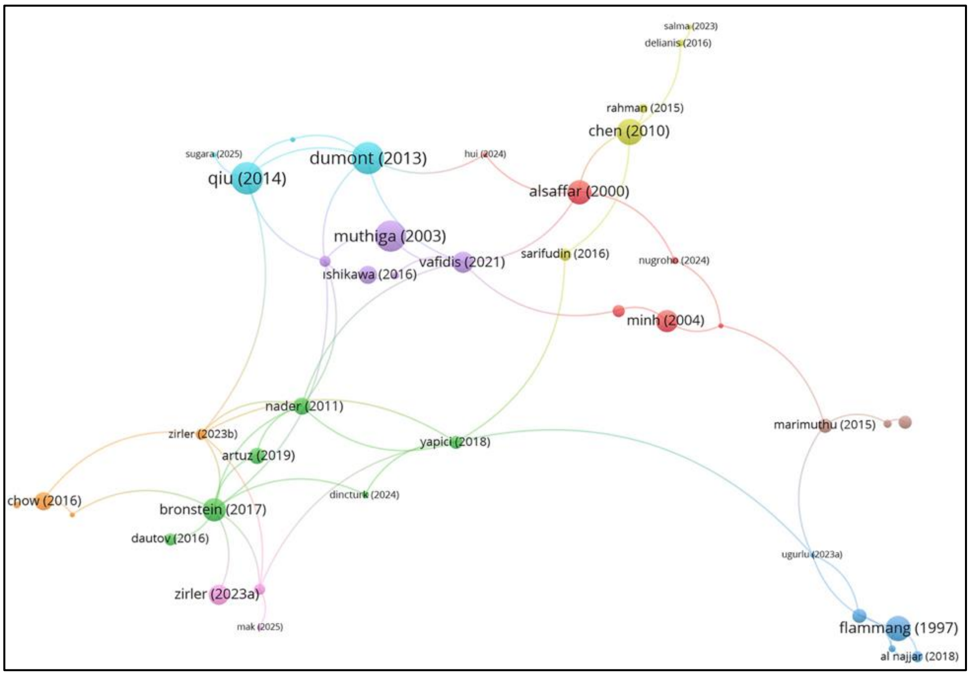

Figure 6. Citation network of *Diadema setosum* publications (1980-2025). Nodes represent individual publications (≥1 citation) and their size is proportional to the number of citations. Links indicate co-citation relationships and reveal the main highly cited studies at the center of the field (such as Bronstein et al., 2017; Roth et al., 2024).

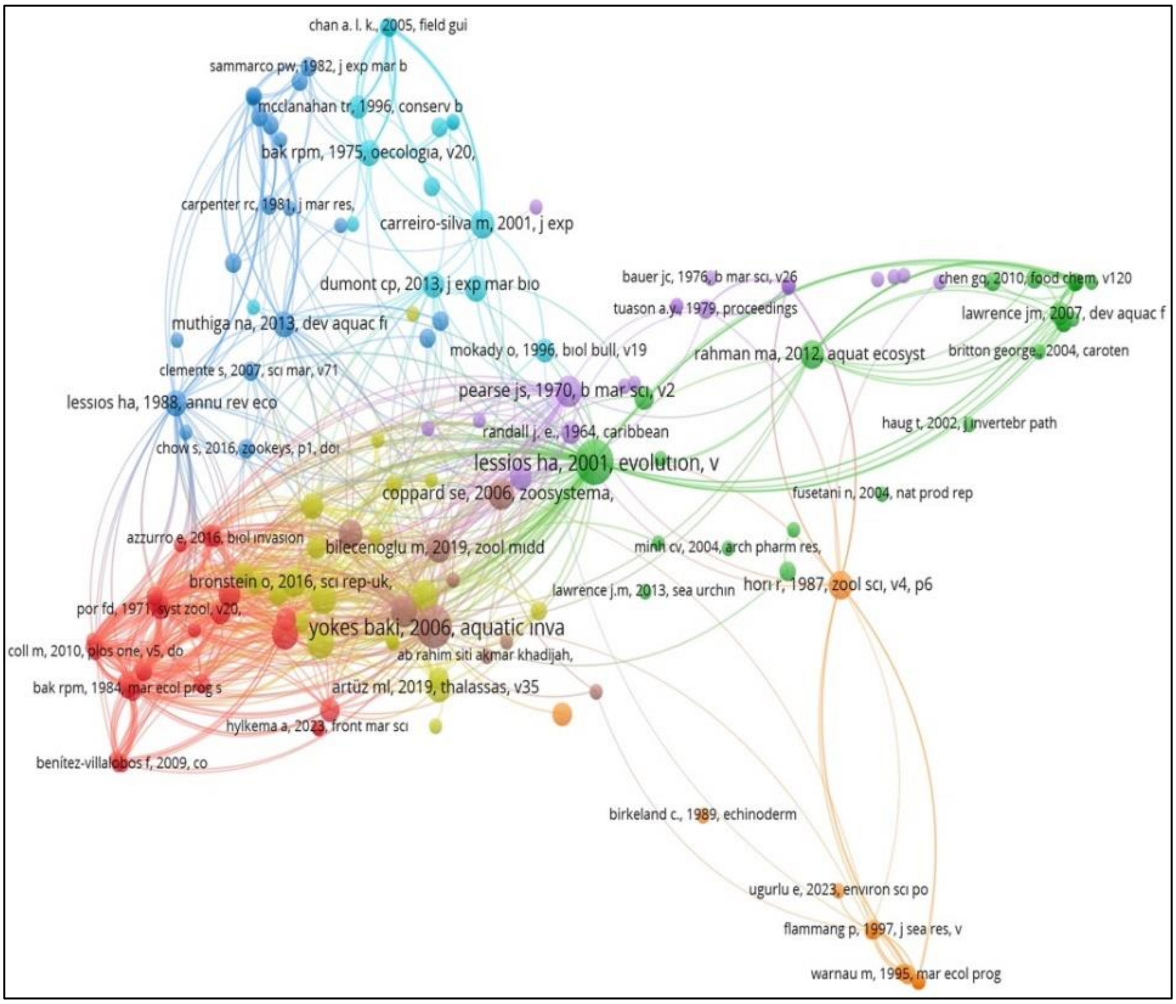

Figure 7. Co-citation network of cited references in *D. setosum* research (1980-2025)

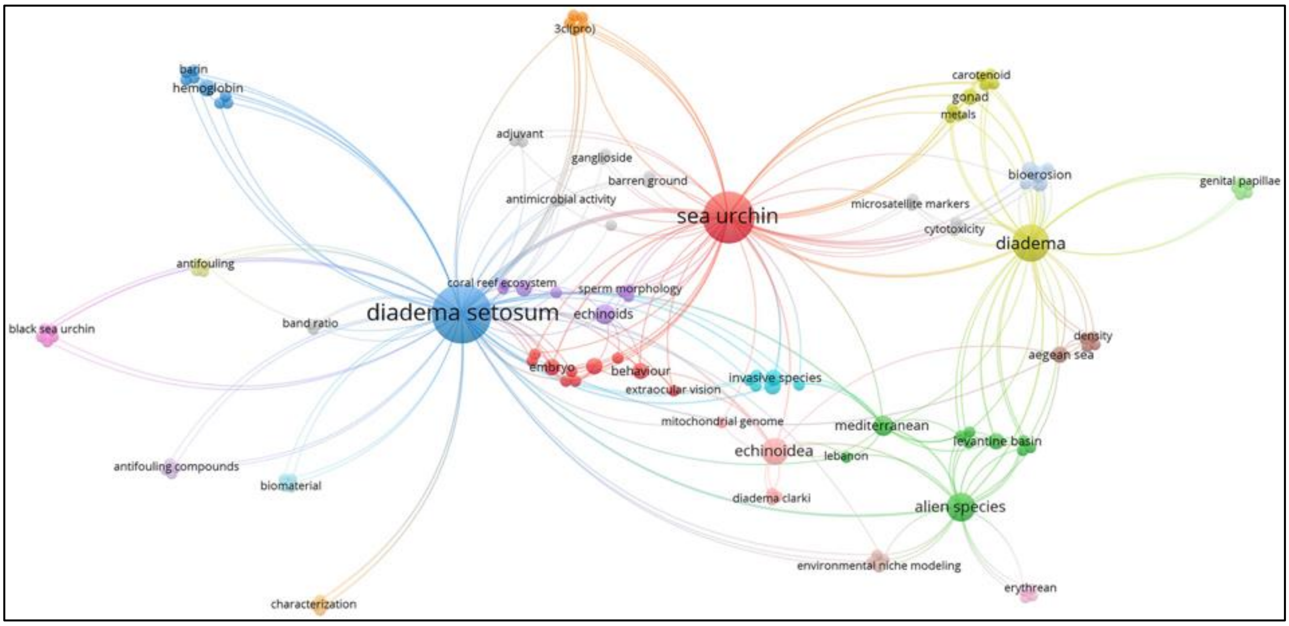

Figure 8. Keyword co-occurrence network for *D. setosum*. Node size reflects frequency, while color-coded clusters denote thematic groupings (such as invasion ecology, ecotoxicology, biomaterials). Total link strength quantifies keyword interconnectivity across publications.

Ecotoxicology and Biomaterials (Emerging Links)

Although less dense in terms of link strength, researchers such as Flammang et al. (1997) and Al Najjar et al. (2018) are included in environmental clusters linking toxicological monitoring to environmental risk assessments. Biomaterial-focused studies (Uğurlu & Duysak, 2023; Uğurlu et al., 2023b, 2023c) point to the early stages of interdisciplinary cross-connections, showing common citation links with engineering-focused journals.

However, the bibliometric density around ecotoxicology and biomaterial applications remains weak, reinforcing the need to include these themes in the core citation network through interdisciplinary collaboration.

Keywords Analysis

When examining the keywords used in scientific publications related to *D. setosum*, it was determined that the species name "*Diadema setosum*" was used 25 times, making it the most frequently used keyword. This keyword is followed by "sea urchin" (n=19) and "diadema" (n=10). Other prominent keywords include "alien species" (n=6), "echinoidea" (n=5), "Mediterranean" (n=3), 'echinoids' (n=3) and "bioerosion" (n=2) (Figure 8).

In addition, themes such as "coral," "platygra," "marine ecology," "invasive species," "behavior," "development," "embryo," "Levantine Basin," "Aegean Sea," "gonad," "heavy metals" and "hemoglobin" are also mentioned twice in the literature. When examining the total link strength of the keywords, it is observed that the terms "sea urchin" (38) and "*Diadema setosum*" (35) have the highest level of correspondence with other concepts (Figure 8). This distribution indicates that the taxonomic identity, biogeographic distribution and environmental impacts of the species are prominent themes in the literature. At the same time, the keywords point to multidisciplinary topics related to the species, such as toxicology ("heavy metals," "hemoglobin"), developmental biology ("embryo," 'development') and ecological impacts ("marine ecology," "bioerosion," "invasive species") (Figure 9).

DISCUSSION

Bibliometric analysis methods have been widely used to identify global research trends (Bornmann & Leydesdorff, 2014; Alvarado & Fabregat Malé, 2021; Ghani et al., 2022; Mao et al., 2023; Zamani et al., 2025). In particular, areas of research concentration, clustering methods and co-citation analysis techniques have been extensively applied in previous studies. The results of our analysis show that global research trends related to the *D. setosum* species exhibit significant parallels and discrepancies when compared to previous bibliometric studies. In studies specifically conducted on *D. setosum*, the exponential population increase after 2014, following the "invasion lag" period, occurred after the species' entry into the Mediterranean (Bronstein et al., 2016; Dautov et al., 2020; Mohd Ramzi et al., 2023; Zirler et al., 2023a, 2023b; Mak et al., 2025; Sugara et al., 2025; Tavoloni et al., 2025). These bibliometric results indicate a significant increase in the number of publications during this period. This aligns directly with the population explosion reported in the literature and the increased geopolitical ecological interest.

Within this global trend, the increase in reports on the widespread distribution of *D. setosum* along the Aegean and Eastern Mediterranean coasts after 2014 supports the rise in the number of publications in bibliometric graphs and suggests that it may have contributed to the overall increase in research outputs on regional geoecological events (Bronstein et al., 2016; Dautov et al., 2020; Mohd Ramzi et al., 2023; Zirler et al., 2023a, 2023b; Vimono et al., 2023; Mak et al., 2025; Sugara et al., 2025; Tavoloni et al., 2025). However, studies on *D. setosum* in the literature are still generally insufficient in terms of geographical distribution analyses and the weakness of international collaboration networks. For example, attention has been drawn to the lack of global-level inter-country collaboration maps. In analysis, despite the high number of Türkiye-based studies, the low number of citations indicates a lack of international visibility. In contrast, similar studies have shown that countries such as the US, China, and the UK are stronger in terms of both publication numbers and citations.

The sudden increases and decreases observed during the analysis are directly related to the "invasion lag" and subsequent rapid population spread dynamics frequently described in the literature. For *D. setosum*, the entry into an exponential spread phase in 2018, particularly in the Eastern Mediterranean, following a prolonged period of low case reports between 2006 and 2017, is defined in the literature as a "biological invasion burst" (Bronstein et al., 2017; Zirler et al., 2023b). Parallel to this situation, the sudden increase in publications observed in our study after 2018 reflects both the ecological spread of the species and the increase in scientific interest. Mass mortality events reported in the literature and the increase in the rate of invasive spread also support this situation (Zirler et al., 2023a; Roth et al., 2024; Skouradakis et al., 2024).

Furthermore, events such as the mass deaths reported in 2023-2025 support the idea that interest increased during this period (Zirler et al., 2023a; Roth et al., 2024; Skouradakis et al., 2024). In contrast, the relative decline experienced in the 2020-2022 period reflects a temporary decline in scientific production due to disruption of fieldwork and international collaborations caused by the Covid-19 pandemic. The literature often refers to the shift of research areas and intensity to other areas after extraordinary events such as pandemics.

These patterns can be explained by the concepts of "citation bursts" and "topic bursts," which have been observed not only in the case of *D. setosum* but also in general bibliometric analyses. This approach highlights sudden trend changes within time series and is explained and supported by algorithmic clustering techniques used by researchers such as Stephen Chan in the literature (Ghani et al., 2022; Mao et al., 2023; Zamani et al., 2025). Therefore, when comparing the analysis findings with similar patterns in the literature, the sudden increases and decreases identified can be interpreted as a combination of both ecological events and temporary pauses in the global academic system.

Table 1. Country-level performance metrics for *D. setosum* research (1980-2025). Indicators include number of documents, total citations and bibliometric link strength (calculated via VOSviewer). These metrics highlight regional dominance (such as Japan, USA) and emerging contributions from Eastern Mediterranean

Country	Documents	Citations	Total Link Strength	Country	Documents	Citations	Total Link Strength
Japan	9	95	2	*Italy*	1	5	4
China	7	124	5	*Canada*	1	0	3
Indonesia	7	15	1	*England*	1	0	3
Greece	5	68	11	*USA*	1	0	3
*Türkiye**	5	9	4	*Netherlands*	1	17	2
Malaysia	5	22	1	*Belgium*	1	26	1
*Turkey**	4	31	1	*Scotland*	1	5	1
Israel	2	22	6	*South Korea*	1	20	1
Austria	2	27	5	*Thailand*	1	0	1
Egypt	2	11	5	*Vietnam*	1	20	1
Russia	2	8	1	*Jordan*	1	5	0
Singapore	2	26	1	*Kenya*	1	41	0
India	2	16	1	*Kuwait*	1	24	0
Cyprus	1	5	4	*Lebanon*	1	13	0
Libya	1	5	4	*Oman*	1	13	0
Malta	1	5	4				

Note: *Studies conducted before 2021 are listed under Turkey, while those after 2021 appear under Türkiye, reflecting the name update.

The analysis findings show that studies on the *D. setosum* species in the global arena are largely conducted in a single center and that international project collaborations are limited. This situation suggests that countries in the Eastern Mediterranean, such as Türkiye, Lebanon, and Israel, are more isolated within the collaboration clusters mapped in the literature. There are studies in the literature that clearly demonstrate the concentration of authors and countries in global scientific network analysis through the analysis of collaboration groups (Bronstein et al., 2017; Vafidis et al., 2021).

Thematic Clustering and Scientific Foci Based on Bibliometric Analysis

Ecotoxicology

It has been determined that there are only a limited number of studies in the literature on metal accumulation in *D. setosum* tissues or shells (Minn et al., 2004; Huseini et al., 2021; Sawalman et al., 2021; Uğurlu, 2023; Tavoloni et al., 2025). However, some studies have focused on the mineral composition and chemical analysis of sea urchin gonads (Kaneko et al., 2009; Bronstein et al., 2017; Ghallab et al., 2024; Hong Kong Biodiversity Genomics Consortium, 2024). Additionally, collagen-based materials obtained from *D. setosum* shells have been used in metal removal studies. It has been demonstrated that Pb (II) ions can be rapidly, effectively, and stably removed from water using alginate-modified collagen beads (Uğurlu et al., 2023c). The number of studies that include analyses of toxic compound potential and environmental metal accumulation is quite low, and this area appears to be poorly represented bibliometrically. This indicates a gap in the field of ecotoxicology, and further research in this area is recommended for the future.

Habitat and Ecological Pressures (Habitat Loss)

Various studies have reported that *D. setosum* is naturally found in high densities in reef and rocky habitats, and in relatively low densities in seagrass and sandy substrates (Lessios et al., 2001; Öndeş et al., 2022; Ghallab et al., 2024). These habitat preferences are associated with environmental changes such as the degradation of natural habitats and increases in sea water temperature during the species' invasive spread. Additionally, it has been reported that in areas where the species is found in high densities, it can cause biological erosion due to overgrazing, which may also lead to habitat loss (Muthiga & McClanahan, 2007, 2020; Moore et al., 2019). In this context, the relationship between habitat loss and *D. setosum*'s habitat preferences, as well as ecological and structural habitat changes, is showing an increasing trend in the literature.

Genetics, Phylogeny, Evolution and Population Structure

Genetic and phylogeographic analyses are emerging as an important area of development in *D. setosum* research. Periodically published studies based on the COI gene indicate that the two clades of the species are linked to their geographical distribution (Lessios et al., 2001; Vimono et al., 2023; Ghallab et al., 2024; Hong Kong Biodiversity Genomics Consortium, 2024; Shahid & Hassan, 2024). A comprehensive study conducted in 2023 clearly identified the source of the invasion and the direction of spread by showing that the *D. setosum* clade detected in the Mediterranean belongs to a single Red Sea clade (Bronstein et al., 2017; Shahid & Hassan, 2024). Such genetic data contribute to the understanding of evolutionary phylogeny and also establish scientific foundations for invasion biology.

Evaluation as a Biomaterial

The biomaterial potential of *D. setosum* has become increasingly visible in the literature in recent years due to growing interdisciplinary studies. The calcium carbonate ($CaCO_3$) found in the shell, spines, and Aristotle's Lantern structures of this species, particularly its low-loss dielectric properties and high crystalline structural order, make this organism noteworthy in the field of biomaterials science (Uğurlu & Duysak, 2023; Uğurlu et al., 2023b, 20023c; Uğurlu, 2023; Mansjur et al., 2025). Studies have revealed the microstructure of *D. setosum* shells using advanced analytical methods such as SEM, XRD, and FTIR (Uğurlu, 2023). These structures possess bioceramic and piezoelectric properties that could potentially be evaluated in fields such as bone tissue engineering, biosensors, and microelectronic devices (Wu et al., 2022; Uğurlu et al., 2023b). Additionally, high-yield chitin and chitosan extraction has been achieved from *D. setosum* spines and shells. In an experimental study conducted by Uğurlu & Duysak (2023), chitosan obtained from the species was evaluated in the category of environmentally friendly biopolymers and reported to have been obtained with a deacetylation degree of over 85%.

In addition, Type I collagen isolated from this species has been proposed as a tissue support material and its potential for use in biomedical fields such as wound coverage and skeletal repair has been indicated (Uğurlu et al., 2023b). Based on this information, it has been demonstrated that *D. setosum* can be considered not only an invasive species but also a sustainable source of biomaterials.

CONCLUSION

This study provides a comprehensive overview of the research history of the *D. setosum* species by systematically analyzing the scientific literature published between 1980 and 2025 using bibliometric methods. Based on 213 academic studies obtained from the Web of Science database, the analysis mapped publication trends, prominent research themes, geographical distribution, author and institutional networks, and intellectual clusters in detail.

When publication numbers were examined by year, a significant increase was observed after 2014, despite the low number of articles published between 2006 and 2014. This period represents a turning point in global bibliometric activity. Genetics, invasion processes, and ecological impacts stand out among the research clusters. However, it has been determined that while the research is thematically focused on genetics and distribution, there is a serious lack of work in areas such as ecotoxicology, biomaterial applications and microplastic exposure.

When examined in terms of geographical distribution, the vast majority of publications are concentrated in Eastern Mediterranean countries, with studies based in Türkiye, Israel and Lebanon being particularly noteworthy. In contrast, it has been found that large-scale collaborative publications based in the US, China or Europe is quite limited. This reveals an imbalance in geographical representation in the literature. When international collaborations are examined, it is observed that these studies are largely limited to the regional level and although countries such as Türkiye, which are located in the current distribution areas of the species, contribute to the research, the citation impact is low. This situation points to structural deficiencies in terms of both scientific visibility and integration into global knowledge networks.

FUTURE PERSPECTIVES

Based on the results of the bibliometric analysis conducted, the following future opportunities and areas of focus have been listed for *D. setosum* research.

Thematic Deepening and Diversification

The existing literature focuses mainly on distribution, genetic structure and ecological effects, while interdisciplinary studies such as ecotoxicological tests, microplastic transport, pathogenic infections and biomaterial production are lacking. Conducting studies focused on these areas will enhance the scientific value of the species and highlight the necessity of research on the sustainable use of *D. setosum* populations in nature.

Expanding International Collaborations

In regions where the species has become invasive, such as Türkiye, Israel, Greece and Lebanon, multi-center projects supported by molecular ecology, isotope analysis and metagenomic studies will contribute to ecosystem-based decision-making mechanisms and increase citation visibility.

Data Sharing and Open Science Applications

Sharing the obtained data on open-source data platforms (e.g., Echinobase, Dryad) will both strengthen the reproducibility of research and enable data-driven modeling.

Expansion of Biotechnological Applications

Advanced experimental studies such as the characterization of the functional properties of biomaterials such as chitin, chitosan, and collagen obtained from *D. setosum* for antimicrobial and biomedical applications are important in terms of both academic and industrial collaborations.

Global Monitoring and Early Warning Systems

Considering the spread rate of the species, mortality patterns, and effects on the habitat, the integration of invasive organisms such as *D. setosum* into early warning systems and long-term monitoring studies are of great importance not only from a scientific perspective but also from a management perspective.

Compliance with Ethical Standards

Authors' Contributions

EU: Conceptualization, Writing – original draft, Investigation, Methodology, Formal Analysis

ÖD: Conceptualization, Writing – review & editing

All authors read and approved the final manuscript.

Conflict of Interest

The authors declare that there is no conflict of interest.

Ethical Approval

For this type of study, formal consent is not required.

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Data Availability

The study was conducted using articles accessed via Web of Science and then processed using VOSviewer software.

AI Disclosure

The authors confirm that no artificial intelligence was used in the creation of the images, tables or figures in this article.

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Statistical Characterization of Residual Interannual Fluctuations for Sea Level From ARIMA Modeling of Adjusted NOAA Data

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ABSTRACT

Sea level rise, a critical consequence of global climate change, poses significant challenges to coastal communities worldwide. While long-term trends in sea level rise garner considerable attention, understanding and predicting interannual variability fluctuations are equally crucial for effective coastal management and adaptation. This research investigates detrended annual variability of adjusted sea level data, focusing on the unpredictable fluctuations superimposed on long-term trends. By employing Autoregressive Integrated Moving Average (ARIMA) modeling, this study aims to quantify and forecast these interannual variations, providing a statistical baseline that underscores the challenge of interannual variability prediction for coastal management. Utilizing adjusted annual sea level measurements from the National Oceanic and Atmospheric Administration (NOAA) spanning 1993 to 2019, this research isolates residual interannual fluctuations by removing the influence of long-term trends and other components through data adjustment. This adjustment process, typically incorporating corrections for factors like glacial isostatic adjustment (GIA) and vertical land motion (VLM), enables a focused analysis of the residual fluctuations. The adjusted sea level data was imported into the Minitab web platform for analysis. The "Forecast with Best ARIMA Model" tool within Minitab's "Stat" menu was employed to automatically identify, fit and diagnose the most appropriate ARIMA model. This tool explores a range of potential ARIMA models, varying the order of autoregressive (AR), integrated (I) and moving average (MA) components, using the Akaike Information Criterion with correction (AICc) to select the best-fitting model while penalizing complexity. The results of this analysis reveal that, after an extensive screening of the ARIMA parameter space, the ARIMA(0,1,0) model, also known as the random walk with drift, emerged as the optimal representation of the adjusted sea level data. This suggests that the residual interannual variability, after accounting for factors removed during data adjustment, is largely unpredictable within the ARIMA framework. The selected model was then used to generate 100-year forecasts, from 2020 to 2119, along with 95% confidence intervals to quantify forecast uncertainty. The standard error of the forecasts was also analyzed, revealing a clear increase in uncertainty with longer forecast horizons. In conclusion, this research demonstrates that while the adjusted sea level exhibits significant annual variability, this variability is largely unpredictable using ARIMA models. This finding underscores the importance of separating the analysis of these kinds of fluctuations from the long-term sea level rise trend, which must be modeled using different approaches. The 100-year forecasts and associated confidence intervals provide valuable information for coastal communities to better prepare for and manage the risks associated with interannual sea level fluctuations, even if precise predictions are not possible. Concurrence of AICc, AIC and BIC provide strong support for validity of the model, reinforces the principle of parsimony, suggests genuine random walk behavior in the adjusted sea level data and increases confidence in the interpretation of the results. While the ARIMA(0,1,0) serves as a robust baseline for understanding the inherent unpredictability of adjusted sea level variations, future research could explore the potential of incorporating predictors, such as climate indices or employing non-linear time series models to further refine understanding and predictive capabilities concerning interannual sea level changes.

INTRODUCTION

Sea level rise stands as one of the most pressing and multifaceted challenges of the 21st century, posing significant threats to coastal communities, ecosystems, and global economies. The intricate interplay between a warming climate, melting ice sheets, thermal expansion of ocean water, and vertical land motion contributes to a complex tapestry of sea level changes that demand careful observation, analysis, and prediction (Priestley et al., 2021; Durand et al., 2022). There is a critical need to explore the aspect of detrended annual variability sea level variability, recognizing that understanding these fluctuations around long-term trends is crucial for effective adaptation and resilience in the face of a changing climate (Shaw et al., 2024). Herein, the 'short-term' refers to interannual variability, as the use of annual data inherently aggregates and removes higher-frequency signals such as seasonal cycles, tides, and storm surges. The scientific consensus regarding the reality and accelerating pace of global warming is unequivocal. The Intergovernmental Panel on Climate Change (IPCC), in its Sixth Assessment Report (AR6), unequivocally states that "it is unequivocal that human influence has warmed the atmosphere, ocean and land" (IPCC, 2021). This warming trend, primarily attributed to anthropogenic greenhouse gas emissions, has profound implications for the Earth's climate system, driving changes in temperature, precipitation patterns, and, critically, sea levels (IPCC, 2021; Priestley et al., 2021). The primary drivers of global mean sea level rise are thermal expansion of ocean water as it warms, melting of glaciers and ice sheets, and changes in land water storage (Durand et al., 2022). While the long-term trend of sea level rise is a dominant feature and a focus of much research, the inherent variability of sea level on shorter timescales also plays a critical role in shaping coastal vulnerability (Shaw et al., 2024).

The IPCC AR6 highlights the alarming projections of future sea level rise, with global mean sea level expected to rise between 0.44 meters and 0.76 meters (17.3 inches and 29.9 inches) by 2100 relative to 1995-2014 under intermediate greenhouse gas emission scenarios (SSP2-4.5) (IPCC, 2021). These projections underscore the urgency of adapting to the inevitable impacts of sea level rise. However, the challenge lies not only in anticipating the long-term trend but also in managing the day-to-day, seasonal, and interannual fluctuations that can exacerbate the impacts of the rising mean sea level. These short-term variations, often driven by factors like tides, storm surges, El Niño-Southern Oscillation (ENSO) events, and local meteorological conditions, can lead to extreme water levels that cause coastal flooding, erosion, and damage to infrastructure However, the challenge lies not only in anticipating the long-term trend but also in managing the interannual fluctuations that can exacerbate the impacts of the rising mean sea level. These climatic and oceanographic variations, often driven by factors like tides, storm surges, El Niño-Southern Oscillation (ENSO) events, and local meteorological conditions, can lead to extreme water levels that cause coastal flooding, erosion, and damage to infrastructure.

(Oppenheimer et al., 2019; Sweet et al., 2022). Coastal communities are particularly vulnerable to the combined effects of long-term sea level rise and interannual variability. As the mean sea level rises, even minor fluctuations in water level can push coastal areas beyond critical thresholds, leading to increased frequency and severity of flooding events. This heightened vulnerability necessitates a comprehensive understanding of both the long-term trends and the interannual variability of sea level to inform effective adaptation strategies. Coastal planning and management decisions, including land use planning, infrastructure development, and disaster preparedness, require accurate and reliable information about the range of potential sea level changes, encompassing both the gradual rise and the more immediate fluctuations.

Traditional approaches to sea level analysis often focus on estimating and projecting long-term trends, providing valuable information for assessing long-term risks and planning for future sea level rise. However, these approaches may overlook the crucial role of interannual variability in shaping immediate coastal vulnerability. Understanding the magnitude and characteristics of these fluctuations is essential for developing effective strategies to mitigate the impacts of extreme water levels and protect coastal communities from near-term hazards. This research addresses this critical gap by focusing specifically on the analysis and forecasting of interannual sea level variability.

The importance of this research is further underscored by the challenges associated with accurately predicting sea level changes in both long and short timescales. While significant progress has been made in understanding the drivers of global mean sea level rise, projecting regional sea level changes and interannual fluctuations remains a complex undertaking. Regional sea level is influenced by a combination of global factors, such as thermal expansion and ice melt, and regional processes, including vertical land motion (VLM) due to geological and anthropogenic factors, ocean currents, and local meteorological conditions (Bromirski et al., 2003; Wöppelmann & Marcos, 2016). VLM, which can cause land to subside or uplift, is a particularly important factor in determining the relative sea level change experienced by coastal communities. Accurately accounting for VLM is crucial for interpreting local sea level measurements and making reliable projections. Furthermore, interannual sea level variability is influenced by a complex interplay of factors, some of which are inherently unpredictable. While tides are a predictable component of sea level variation, other factors, such as storm surges and ENSO events, are more challenging to forecast (McPhaden et al., 2006). Storm surges, generated by strong winds and low atmospheric pressure, can cause significant deviations from predicted tidal levels, leading to coastal flooding. ENSO events, characterized by fluctuations in sea surface temperatures in the Pacific Ocean, can also influence regional sea levels through their impact on weather patterns and ocean currents. These complexities highlight the need for sophisticated statistical techniques to analyze and model interannual sea level variability.

This research employs a time series analysis approach, utilizing the Autoregressive Integrated Moving Average (ARIMA) modeling framework, to investigate the interannual variability of adjusted sea level data. ARIMA models are a class of statistical models widely used for analyzing and forecasting data from time series (Box et al., 2015; Hyndman & Athanasopoulos, 2018). They are particularly well-suited for capturing the complex dependencies and patterns in geophysical time series, including sea level fluctuations (Pugh & Woodworth, 2014; Box et al., 2015). They (ARIMA models) are particularly well-suited for capturing the complex dependencies and patterns that characterize sea level fluctuations (Box et al., 2015; Hyndman & Athanasopoulos, 2018). Critically, the sea level data used in this study has been adjusted to remove the influence of long-term trends and other predictable components, allowing us to isolate and focus specifically on the interannual variability. This adjustment process typically involves removing the estimated contributions of factors like glacial isostatic adjustment (GIA) and vertical land motion (VLM), effectively detrending the data (Peltier, 2004; Wöppelmann & Marcos, 2016; NOAA, 2022). By analyzing the residual variability after these adjustments, we aim to gain a clearer understanding of the unpredictable interannual fluctuations that are superimposed on the long-term trend. A key objective of this research is to identify the best-fitting ARIMA model that adequately captures the statistical characteristics of the adjusted sea level data. We employ a rigorous model selection procedure, exploring a wide range of ARIMA models with different orders of autoregressive (AR) and moving average (MA) components and different levels of differencing (I). The Akaike Information Criterion with correction (AICc) is used to compare the goodness-of-fit of different models, penalizing model complexity to avoid overfitting (Hyndman & Khandakar, 2008). This extensive screening of the ARIMA parameter space allows us to confidently select the most parsimonious model that adequately represents the observed interannual variability. This research also addresses the critical issue of forecast uncertainty. Given the inherent unpredictability of some of the factors influencing sea level, it is essential to quantify the uncertainty associated with any sea level forecast. We utilize the selected ARIMA model to generate long-term forecasts of adjusted sea level and compute confidence intervals around these forecasts. These confidence intervals provide a measure of the range of plausible future sea level fluctuations, allowing coastal communities to assess and manage the associated risks.

The central question that this research seeks to answer is: What is the nature and predictability of interannual sea level variability after accounting for long-term trends and other predictable components? By addressing this question, we aim to provide valuable information for coastal planning and management, infrastructure design, and emergency preparedness (Nicholls et al., 2014; Pugh & Woodworth, 2014). Specifically, this research can contribute to: Improved coastal planning: By providing quantitative estimates of interannual sea level fluctuations, this research can help coastal communities make informed decisions about land use planning, development setbacks, and the design of coastal defenses. Enhanced infrastructure design: Engineers can utilize the information on potential sea level variability to design coastal infrastructure that is resilient to extreme water levels and coastal erosion. Strengthened emergency preparedness: Emergency managers can use the forecasts and uncertainty estimates to develop and implement effective plans for coastal flooding events, including evacuation strategies and disaster response measures. Ultimately, this research aims to contribute to a more nuanced understanding of the complexities of sea level change and to provide valuable information for building resilient coastal communities in the face of a changing climate. While the focus is on interannual variability, this research also serves to highlight the critical importance of ongoing efforts to understand and project long-term sea level trends, which are essential for addressing the long-term challenges of sea level rise. By disentangling the various components of sea level change, we can develop more effective strategies to mitigate the impacts of rising seas and protect vulnerable coastal populations.

MATERIAL AND METHODS

This research investigates the interannual variability of adjusted sea level using a time series analysis approach. The data source is the National Oceanic and Atmospheric Administration (NOAA) Sea Level Rise Viewer (NOAA, 2022), specifically data accessed from the Digital Coast platform, spanning the years 1993 to 2019, with the data being recorded annually in inches, as it is the standard unit used by NOAA. The period from 1993 to 2019 was selected as it corresponds to the modern altimetry era, providing a consistent, high-quality global dataset.

Data Preparation

The dataset, consisting of annual adjusted sea level measurements, (It's a yearly record focused purely on the random ups and downs of sea level, not its long-term trend) was directly imported into the Minitab web platform. No further transformations or adjustments were deemed necessary as the data was already provided in its adjusted form, pre-processed by NOAA to account for long-term trends and other predictable influences. This pre-adjustment typically includes corrections for factors such as glacial isostatic adjustment (GIA) and vertical land motion (VLM) (Peltier, 2004; Wöppelmann & Marcos, 2016), enabling the analysis to focus specifically on the residual interannual variability. In layman's term, it's like subtracting the movement of the bathtub to measure only the movement of the water inside it. This allows scientists to isolate the true change in sea water height. The annual resolution of the data inherently aggregates within-year fluctuations, effectively excluding any seasonal patterns. Therefore, no further adjustments for seasonality were deemed necessary.

Time Series Analysis

The core of the analysis involved utilizing the ARIMA modeling framework to characterize and forecast the detrended annual fluctuations in the adjusted sea level. ARIMA models are a class of statistical models commonly employed for analyzing and forecasting time series data due to their ability to capture complex dependencies and patterns within the data (Box et al., 2015; Hyndman & Athanasopoulos, 2021). The analysis was conducted using the "Forecast with Best ARIMA Model" tool available within the "Stat" menu of the Minitab web platform. This tool automates the process of identifying, fitting, and diagnosing the most appropriate ARIMA model for the given time series (Minitab LLC, 2023).

Model Identification and Selection

The "Forecast with Best ARIMA Model" tool in Minitab automatically explores a range of potential ARIMA models, varying the order of autoregressive (AR) components (p), integrated (I) components or degree of differencing (d), and moving average (MA) components (q). The tool employs the Akaike Information Criterion with correction (AICc) to guide model selection. AICc is a statistical measure that evaluates the goodness-of-fit of different models while penalizing model complexity. This helps prevent overfitting, ensuring the selected model generalizes well to unseen data (Hyndman & Khandakar, 2008). Minitab's automated tool handles the often-complex task of ARIMA model identification, parameter estimation, and diagnostic checking (Minitab LLC, 2023). Different degrees of differencing levels were compared at d = 0, 1 and 2 to find the most suitable model parameters.

Forecasting

Once the optimal ARIMA model, as determined by the minimum AICc, was identified and fitted, the Minitab tool was used to generate forecasts for the next 100 years (from 2020 to 2119). The "Forecast with Best ARIMA Model" tool automatically calculates point forecasts as well as corresponding confidence intervals, providing a measure of the forecast uncertainty. Specifically, 95% confidence intervals were generated, representing the range within which the true adjusted sea level is expected to lie with 95% probability, assuming the chosen model is adequate (Minitab LLC, 2023).

Software and Platform

All analyses were performed using Minitab's web-based statistical software platform. This platform provides a user-friendly interface and access to powerful statistical tools, including the automated ARIMA modeling and forecasting capabilities used in this research (Minitab LLC, 2023).

RESULTS AND DISCUSSION

The application of statistical analysis software and methods for trend analysis has been demonstrated across diverse fields, including pharmaceutical quality control and disease monitoring, highlighting its versatility in identifying trends and patterns (Eissa, 2018a; Eissa & Abid, 2018; Eissa, 2018b; Eissa, 2018c; Rashed & Eissa, 2020). However, it is important to note that the current study applies different concepts and tools to a unique dataset of adjusted sea level measurements. An ARIMA model selection process was undertaken to forecast adjusted sea level (millimeters) using NOAA data from the Sea Level Rise Viewer (NOAA, 2022). Several ARIMA (p, d, q) models were evaluated, with the Akaike Information Criterion with correction (AICc) serving as the primary metric for model selection, as recommended for smaller sample sizes (Hyndman & Khandakar, 2008). A warning was issued regarding inestimable models, specifically those with d=0 and various combinations of p and q, including (1,0,0) through (5,0,4), and also model (5,1,2) with d=1. These models, which included a constant term, could not be reliably estimated, likely due to limitations in the data or model complexity, a common challenge in time series modeling (Box et al., 2015). The analysis utilized 27 rows of data, with none left unused. Figure 1 shows radar scan screening of various model parameters accompanied by Table 1 for statistical examination and comparative analysis for the best fits at d = 0, 1 and 2.

However, it is important to note that the current study applies these general statistical concepts and tools to a unique dataset of adjusted sea level measurements. For models with no differencing (d=0), the best model, achieving the minimum AICc of -13.2609, was an ARIMA(2,0,0) model (Table 1). This model exhibited statistically significant autoregressive terms, with AR 1 having a coefficient of 1.874 (p<0.000) and AR 2 having a coefficient of -0.876 (p=0.008). The model's residual variance (MSD) was 0.0188886. The Ljung-Box test indicated some potential autocorrelation at lag 12 (p=0.029) but not at lag 24 (p=0.431), suggesting a possible limitation in the model's ability to fully capture the autocorrelation structure at this lag (Ljung & Box, 1978).

When first-order differencing was applied (d=1), the best model, minimizing the AICc to -42.9753, was surprisingly identified as a simple random walk model with a constant term of 0.122021 (ARIMA(0,1,0)). This model's residual variance was 0.0090385. The Ljung-Box test showed no significant autocorrelation at either lag 12 (p=0.252) or lag 24 (p=0.753), indicating that the residuals closely approximate white noise, a desirable characteristic for time series models (Hyndman & Athanasopoulos, 2021). Table 1 shows detailed statistical evaluation of this model.

For second-order differencing (d=2), the best performing model, with the lowest AICc of -36.8726, was an ARIMA(0,2,1) model. This model had a statistically significant moving average term (MA 1) with a coefficient of 0.9974 (p<0.000). After differencing, there were 25 observations. The model's residual variance was 0.0099227. Similar to the d=1 case, the Ljung-Box test showed no significant autocorrelation at lag 12 (p=0.274) or lag 24 (p=0.741). Figures 2 and 3 demonstrate visual comparison between the three models through Autocorrelation Function (ACF) and partial Autocorrelation Function (PACF) of residuals. Then, forecasts were generated from time period 27 onwards for all three best models and the 95% confidence limits were also computed.

In summary, across the three different levels of differencing, three different models were selected as "best" based on AICc. The simplest model, the random walk with drift (ARIMA(0,1,0)), was selected for d=1, implying that the adjusted sea level data, when differenced once, behaves much like a random walk. This suggests that the year-to-year changes are largely unpredictable, which is consistent with findings that interannual sea level variability is complex and difficult to forecast (Sweet et al., 2022). The other two models, ARIMA(2,0,0) for d=0 and ARIMA(0,2,1) for d=2, are more complex. Further investigation of model diagnostics, especially residual analysis and comparison with other forecasting methods, is recommended.

After a thorough search of ARIMA models with d=0, 1 and 2, on addition to considering various combinations of p and q was examined, a single ARIMA model emerges as the most fitting one. The ARIMA(0,1,0) model (random walk with drift) with d=1 has the lowest AICc, indicating that it's the best model within the ARIMA family for adjusted sea level data. The Ljung-Box test on the residuals further supports the model's adequacy (Figure 4). The model suggests that the year-to-year changes in adjusted sea level behave largely like random fluctuations around a long-term trend.

Given an extensive screening of all possible ARIMA parameters (p, d, q) was conducted, the selection of the ARIMA(0,1,0) (random walk with drift) model as the "best" model takes on a different light. While it's still crucial to understand the model's implications and limitations, the extensive search strengthens the argument for its validity within the class of ARIMA models. After an exhaustive search, the simplest model provided the best fit according to

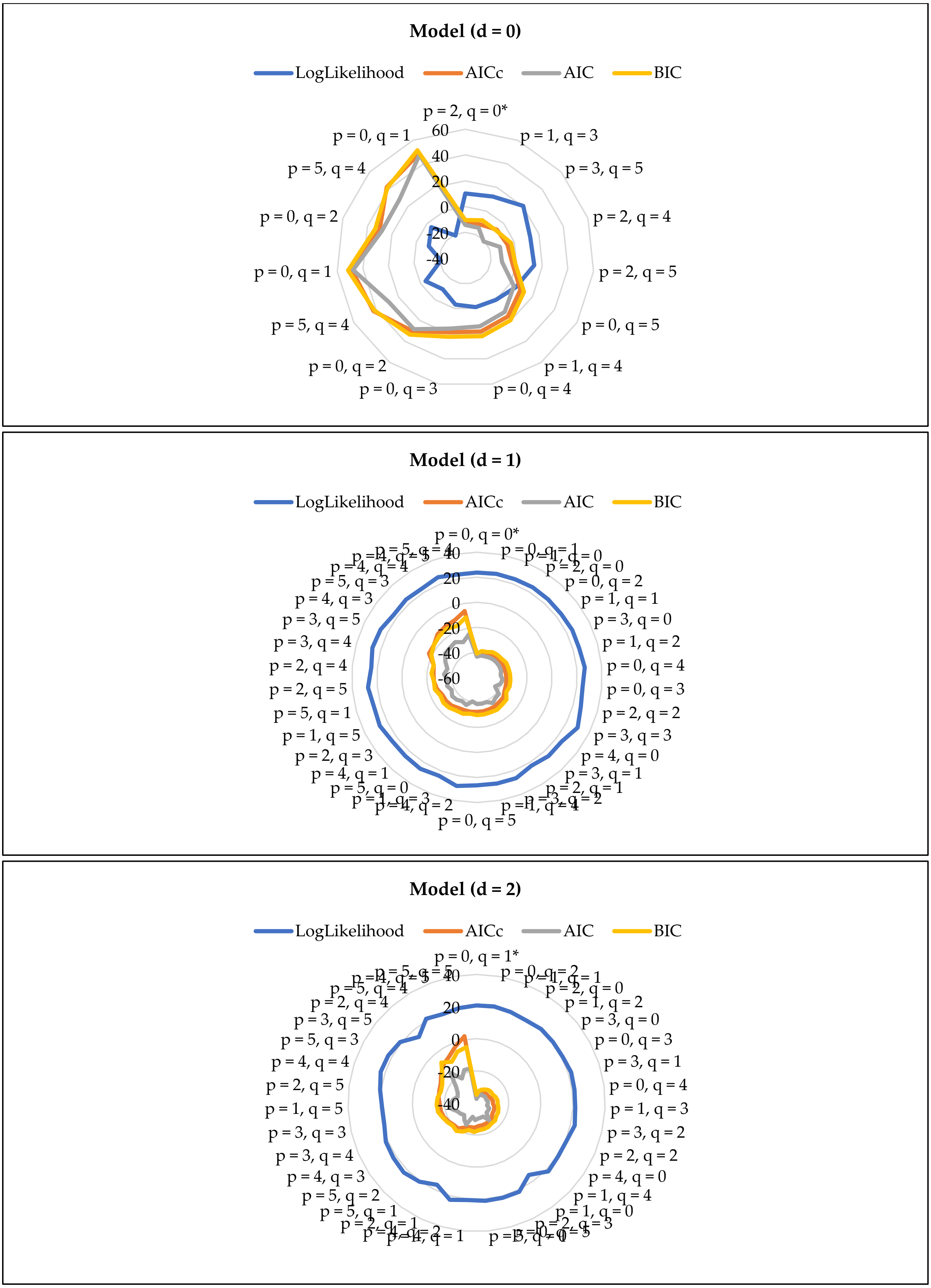

Figure 1. Radar scan chart of the selection of best ARIMA model with minimum AICc. *Denotes the selected model at each d value. For NOAA – adjusted sea level (inches), a model with (0,1,0) is the best fit.

AICc, strongly supporting the principle of parsimony (Hyndman & Athanasopoulos, 2021). It answers the question of why to use a more complex ARIMA model if it does not offer a statistically significant improvement. The lowest AICc value across all tested ARIMA models underscores the relative superiority of the random walk model within this class. The random walk model's success aligns with existing research highlighting the difficulty of predicting interannual sea level fluctuations and the extensive search reinforces the idea that this unpredictability is not simply due to a poorly chosen model within the ARIMA family.

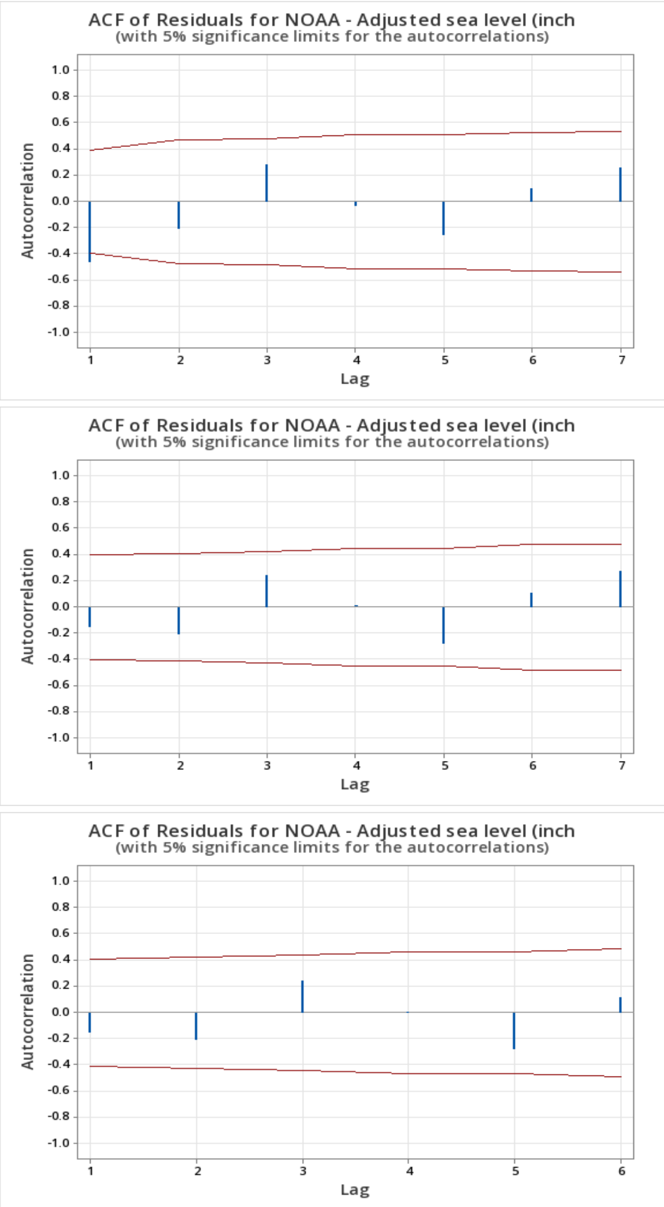

Figure 2. Autocorrelation Function (ACF) of residuals for best models at d =0, 1 and 2 in their respective order from top to the bottom graph at 5% significance level

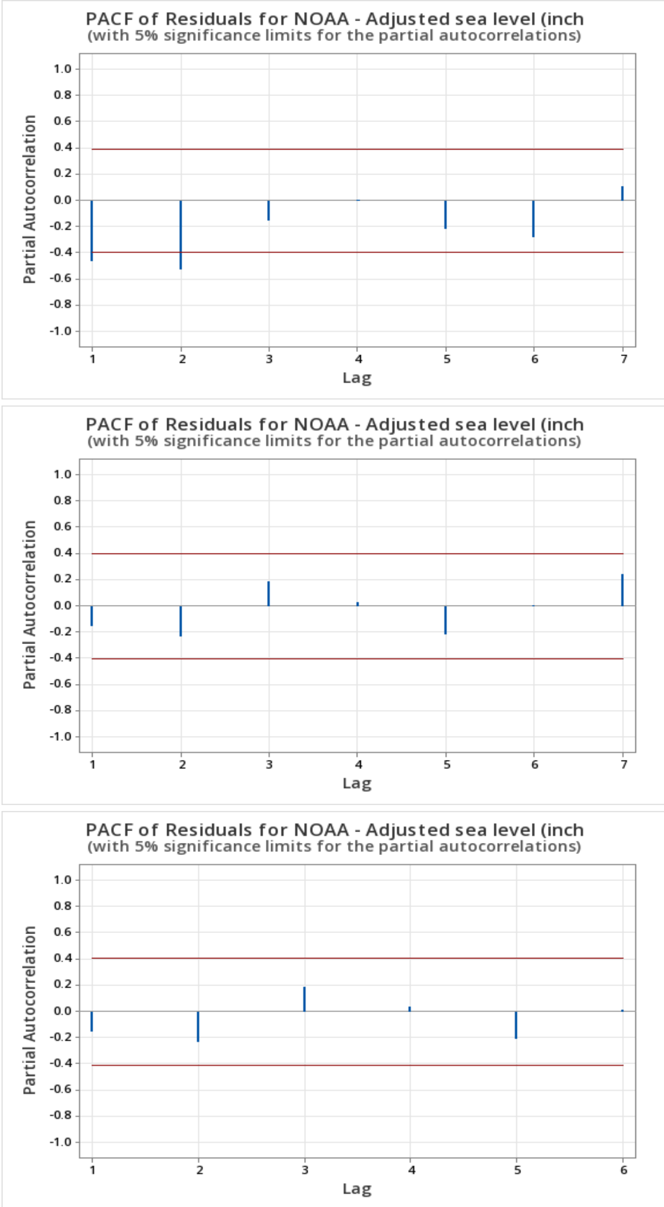

Figure 3. Partial Autocorrelation Function (PACF) of residuals for best models at d =0, 1 and 2 in their respective order from top to the bottom graph at 5% significance level

However, it's important to note that while the ARIMA(0,1,0) model was selected based on AICc, the choice of p and q parameters was not entirely consistent across AIC, BIC and AICc for all differencing orders (d). Specifically, for d=0, while AICc and BIC both favored ARIMA(2,0,0), AIC selected ARIMA(3,0,5). For d=1 and d=2, all three criteria converged on ARIMA(0,1,0) and ARIMA(0,2,1), respectively. This discrepancy at d=0 highlights that while AICc, AIC, and BIC often agree, they can sometimes select different models, especially when the differences in fit are small (Burnham & Anderson, 2002). It's crucial to acknowledge these differences and understand the strengths and weaknesses of each criterion. AICc is generally preferred for smaller sample sizes due to its bias correction, BIC is consistent in selecting the true model with increasing sample size and AIC, while asymptotically efficient, can sometimes over-penalize complex models in small samples. Therefore, while the ARIMA(0,1,0) model emerged as the best based on AICc after an extensive search, the behavior of AIC and BIC, particularly at d=1, provides additional context for model selection.

Despite the extensive search for selection of the best fitting ARIMA model, few questionable issues remain for investigation. For instance, while the random walk model is the best among ARIMA models, it still simplifies the complex reality of sea level dynamics. The success of the random walk model does not imply that interannual variability lacks physical drivers; rather, it suggests that after detrending, the remaining interannual fluctuations for this dataset are not effectively captured by a linear autoregressive or moving average process. The influence of complex, non-linear phenomena like ENSO may be a primary reason for this. However, this simplification is justified within the ARIMA framework given the deep search by screening of the parameters. The random walk model, as applied to adjusted sea level data, describes variability around a trend. The trend itself is a separate and essential component of sea level change and its modeling requires different methods (Church & White, 2011). This separation must be clearly articulated.

Figure 2 displays the Autocorrelation Function (ACF) of the residuals for the best fitting ARIMA models at differencing orders d=0, 1, and 2, presented in order from top to bottom. Examining the ACFs helps assess the adequacy of the fitted models by checking if the residuals resemble white noise, a key assumption of ARIMA models (Box et al., 2015). In the top graph, corresponding to d=0, there's a noticeable spike at lag 1, which falls just outside the 5% significance bounds. This suggests potential autocorrelation at lag 1, indicating that the residuals are not entirely random and that the ARIMA(2,0,0) model might not have fully captured the dependence within the data. Moving to the middle graph (d=1), the ACF shows no significant spikes outside the bounds. All autocorrelations fall well within the 5% significance limits, suggesting that the residuals of the ARIMA(0,1,0) (random walk) model are essentially random. This supports the adequacy of the random walk model for the differenced data at d=1. Finally, the bottom graph, representing d=2, also shows no significant autocorrelations beyond the 5 % bounds. This indicates that the residuals of the ARIMA(0,2,1) model are also random, supporting the model's validity. Thus, while the ACF for d=0 raises some concerns about remaining autocorrelation, the ACFs for d=1 and d=2 suggest that the respective selected models are reasonably adequate, with residuals that approximate white noise.

The Partial Autocorrelation Function (PACF) plots in Figure 3, arranged from top to bottom for d=0, 1, and 2 respectively, offer further insight into the appropriateness of the chosen ARIMA models. The PACF helps determine the order of the autoregressive (AR) component in the model (Box et al., 2015). In the top graph (d=0), the PACF shows a significant spike at lags 1 and 2, which could be expected in an ARIMA(2,0,0) model. This confirms the presence of a direct relationship between the current residual and the residual two periods prior, after accounting for the effect of the intervening lag. The lack of other significant spikes suggests that the AR order is indeed 2. The middle graph (d=1) shows no significant spikes at any lag, consistent with the ARIMA(0,1,0) (random walk) model. This reinforces the idea that, after differencing, there's no remaining autoregressive component needing to be modeled. Finally, the bottom graph (d=2) shows a significant spike at lag 1, which aligns with the ARIMA(0,2,1) model, suggesting a direct relationship between the current residual and the previous residual. The absence of further significant spikes supports the choice of a MA(1) component in the model. Overall, the PACF plots provide additional evidence supporting the selected ARIMA models for each differencing order. The significant spikes at the expected lags confirm the chosen AR orders, while the lack of other significant spikes suggests that the models have adequately captured the dependence structure in the data.

Figure 4 presents a comprehensive residual analysis for the best fitting ARIMA models at differencing orders d=0, 1 and 2, arranged from top to bottom. For each differencing order, the figure includes a normal probability plot, a histogram of the residuals, a plot of residuals versus fitted values and a plot of residuals versus observation order. These plots help assess the validity of the model assumptions, primarily focusing on normality, constant variance (homoscedasticity) and lack of autocorrelation in the residuals, which are fundamental to the validity of ARIMA models (Box et al., 2015). Starting with d=0 (top row), the normal probability plot shows almost no deviation from the straight line, but little at the tails, suggesting low potential of departures from normality. The histogram also indicates a slightly skewed distribution, which can be an indication of model misspecification or outliers (Hyndman & Athanasopoulos, 2021). The residuals versus fits plot shows no clear pattern, suggesting constant variance across the range of fitted values. However, the residuals versus order plot reveals a potential issue: there appears to be some non-randomness, with possible cyclical patterns or trends. For d=0, the residuals versus order plot reveals a potential issue: there appears to be some non-randomness, with possible cyclical patterns or trends. This suggests potential autocorrelation, which contradicts the model assumptions and is consistent with the earlier ACF findings, indicating that the ARIMA(2,0,0) model may not fully capture the time dependencies in the data. This suggests potential autocorrelation, which contradicts the model assumptions and is consistent with the earlier ACF findings, indicating that the ARIMA(2,0,0) model may not fully capture the time dependencies in the data. Figure 4 shows the best fitting ARIMA results for difference orders d=0, 1 and 2 arranged from top to bottom.

For d=1 (middle row), the normal probability plot aligns closely with the straight line, indicating that the residuals are approximately normally distributed. The histogram is also roughly bell-shaped with little skewness, supporting this conclusion. The residuals versus fits plot shows a random scatter of points, suggesting constant variance. The residuals versus order plot exhibits random fluctuations around zero, indicating no apparent autocorrelation. This aligns with the ACF and PACF results and further supports the adequacy of the ARIMA(0,1,0) model. Finally, for d=2 (bottom row), the normal probability plot again shows a reasonable fit to the straight line with minor deviations. The histogram is roughly symmetric. The residuals versus fits plot shows no discernible patterns, suggesting constant variance. The residuals versus order plot displays random variation, indicating no significant autocorrelation.

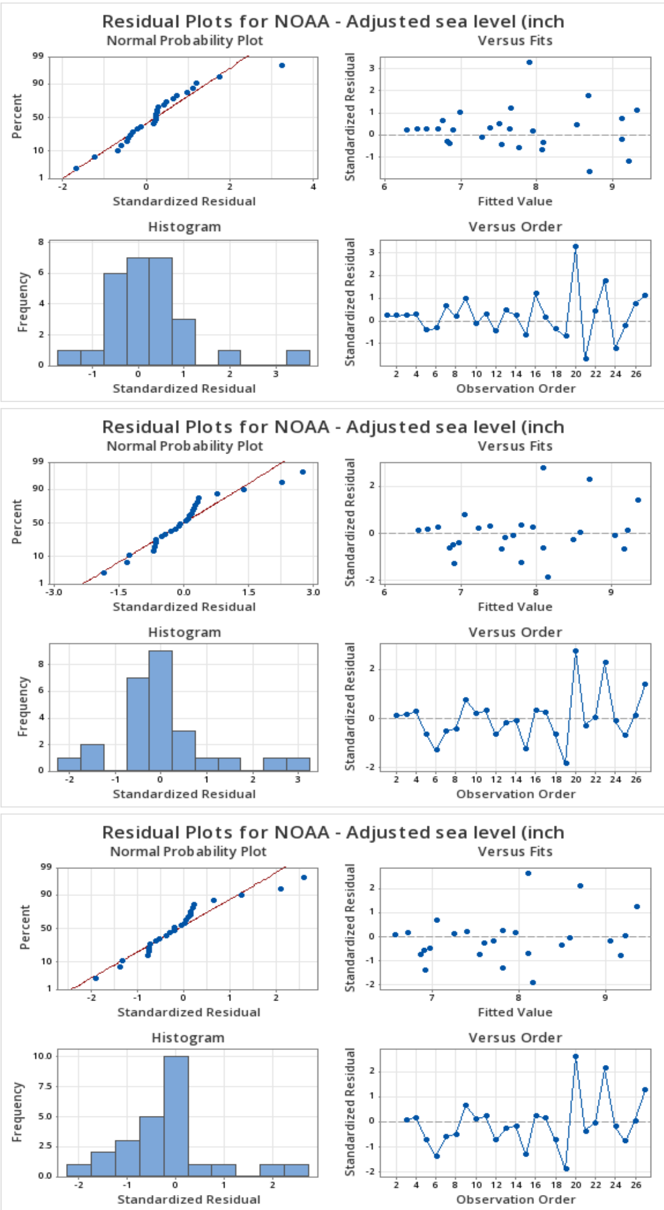

Figure 4. Residual graphical analysis for best ARIMA models at d =0, 1 and 2 in their respective order from top to the bottom graph

Table 1. Statistical analysis and comparison of the best-fitting ARIMA models for differencing orders d = 0, 1, and 2, selected based on minimum AIC_C

Model Identification		**Parameter Estimates**		**Goodness-of-Fit Statistics**				**Residual Diagnostics (Ljung-Box Test)**				
Model (p, d, q)	**Term**	**Coefficient (SE)**	**P-Value**	**Log-Likelihood**	**AIC_C**	**AIC**	**BIC**	**Residual MSD**	**Lag**	**Chi-Square**	**DF**	**P-Value**
ARIMA(2, 0, 0)	Constant	Not Estimated	-	10.15	**-13.26**	-14.30	-10.42	0.0189	12	20.06	10	0.029
	AR(1)	1.874 (0.302)	< 0.001						24	22.49	22	0.431
	AR(2)	-0.876 (0.306)	0.008									
ARIMA(0, 1, 0) (Random Walk with Drift)	Constant (Drift)	0.122	-	23.75	**-42.98**	-43.50	-40.98	0.0090	12	13.66	11	0.252
									24	18.09	23	0.753
ARIMA(0, 2, 1)	MA(1)	0.997 (0.051)	< 0.001	20.71	**-36.87**	-37.42	-34.98	0.0099	12	13.31	11	0.274
									24	18.29	23	0.741

Importantly, the residual analysis paints a mixed picture. For d=1 and d=2, the residuals generally satisfy the assumptions of normality, constant variance and lack of autocorrelation, supporting the selected ARIMA models. However, for d=0, patterns in the residuals versus order plot suggest possible autocorrelation. This casts doubt on the adequacy of the ARIMA(2,0,0) model at d=0 and highlights the importance of considering model diagnostics in conjunction with information criteria like AICc. While AICc suggested the ARIMA(0,1,0) as the best model, at d=1, the residual analysis alone might not show adequate resolution that it is the optimum choice, a demonstration of the importance of using multiple diagnostics in time series analysis (Burnham & Anderson, 2002).

Figure 5 presents 100-year forecasts, from time period 27 onwards, for the adjusted sea level using the selected ARIMA models at d=0, 1 and 2, along with their 95% confidence intervals. The top three plots show the forecast, upper, and lower limits for each differencing order. The bottom plot displays the standard errors (SE) of the forecasts for each model. The forecasts for d=0 (top plot) show a relatively narrow confidence band initially, which widens as the forecast horizon extends. However, the forecast itself appears to decrease over time, which might be counterintuitive for sea level projections and warrants further investigation. This discrepancy could be due to the model's inability to capture the long-term trends in the data, as highlighted by the residual analysis (Church & White, 2011). The forecasts for d=1 (second plot) and d=2 (third plot) show a more typical pattern of widening confidence bands with increasing forecast horizon. Both forecasts generally indicate an upward trend in adjusted sea level, although the specific trajectories differ slightly.

The standard error plot (bottom) confirms the expected behavior of increasing uncertainty with longer forecasts. Importantly, it also shows a clear hierarchy of forecast uncertainty, with SE(d=0) > SE(d=2) > SE(d=1). This indicates that the forecasts from the ARIMA(0,1,0) model (d=1) have the smallest standard errors and thus the highest precision, followed by the ARIMA(0,2,1) (d=2) model, and lastly the ARIMA(2,0,0) (d=0) model, which exhibits the largest forecast uncertainty. This ordering is consistent with the complexity of the models, with the simpler random walk model (d=1) yielding more precise forecasts compared to the more complex models at d=2 and d=0. Hence, Figure 5 provides a long-term perspective on the adjusted sea level forecasts and their uncertainty. The differences in forecast trajectories and uncertainty levels across the three differencing orders highlight the importance of model selection. The finding that the d=1 model (random walk) has the lowest forecast uncertainty, despite its simplicity, reinforces its selection as the preferred model within the ARIMA family for this specific dataset. However, the unexpected downward trend in the d=0 forecast raises concerns and calls for further scrutiny of the model's assumptions and the data at d=0.

Figure 6 provides a holistic view of the adjusted sea level data and the forecasts generated from the ARIMA models at differencing orders d=0, 1, and 2. The plots, arranged from top to bottom, show the historical data up to time period 27, followed by the forecasts and their 95% confidence intervals extending into the future. The top graph (d=0) shows the ARIMA(2,0,0) model's fit and forecast. We can observe how the model attempts to capture the existing trend and variability in the historical data. However, the forecast diverges significantly, showing a downward trend that, as mentioned before, is atypical for sea level projections and may indicate a problem with the model's assumptions or the data at d=0, which may be due to the model not fully capturing the underlying trend.

The middle graph (d=1) displays the ARIMA(0,1,0) (random walk) model's fit and forecast. The historical data, when differenced once, suggests a mean change with random variations around it, hence the random walk captures this nicely. The forecast reflects this, continuing the general upward trend observed in the recent historical data with widening uncertainty bounds, which is typical for random walk models. The bottom graph (d=2) presents the ARIMA(0,2,1) model's fit and forecast. Similar to the d=1 case, the model captures the upward trend in the historical data and projects it forward with increasing uncertainty. However, the specific trajectory and the width of the confidence bands differ slightly compared to the d=1 forecast, reflecting the different model specifications.

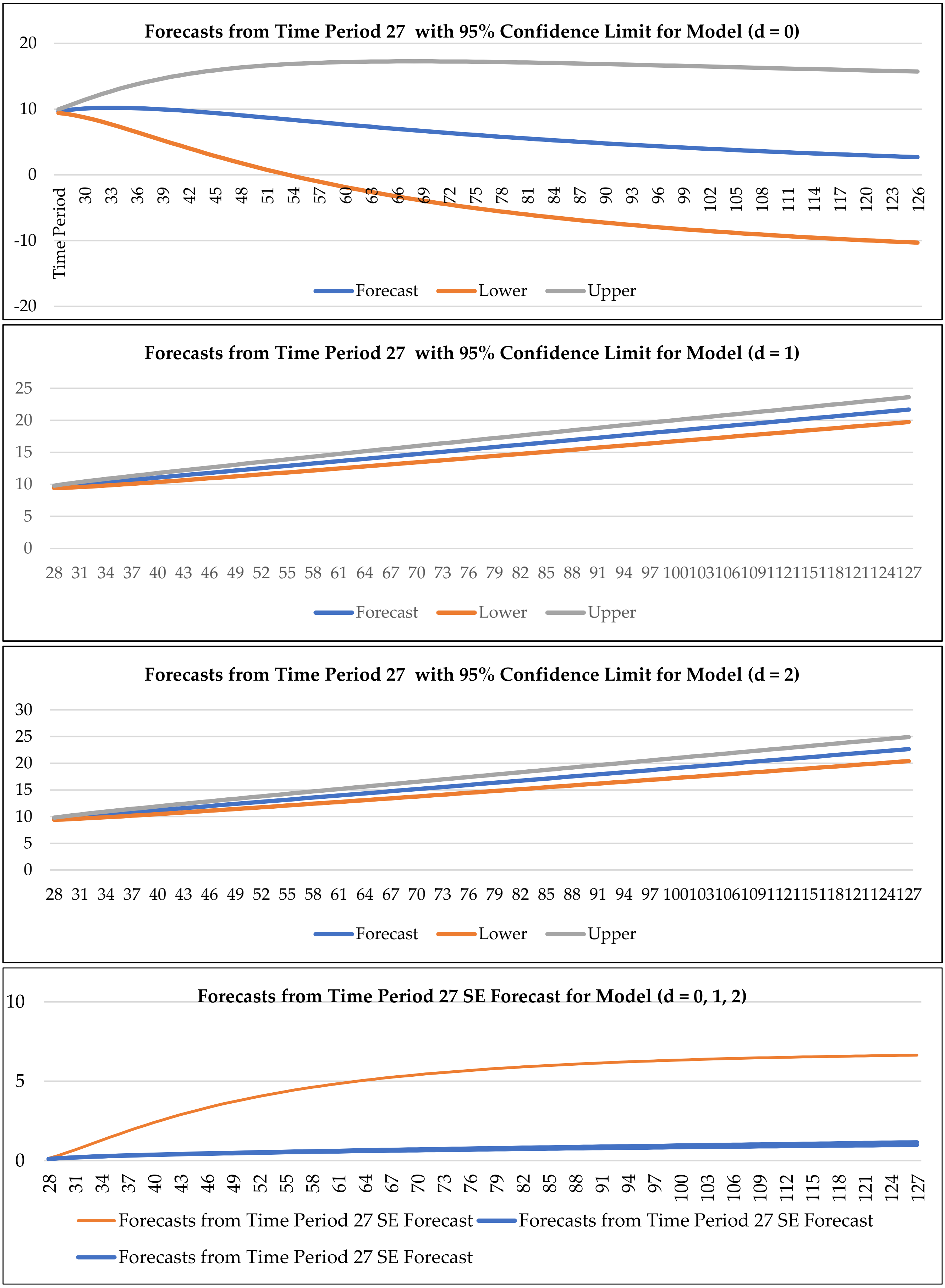

Figure 5. Focused section for forecasting on a yearly basis for 100 years with upper and lower confidence limits with y-axis showing sea level (in inches) and x-axis time (in years). Standard Error (SE) graph shows that values of $SE_0 > SE_2 > SE_1$.

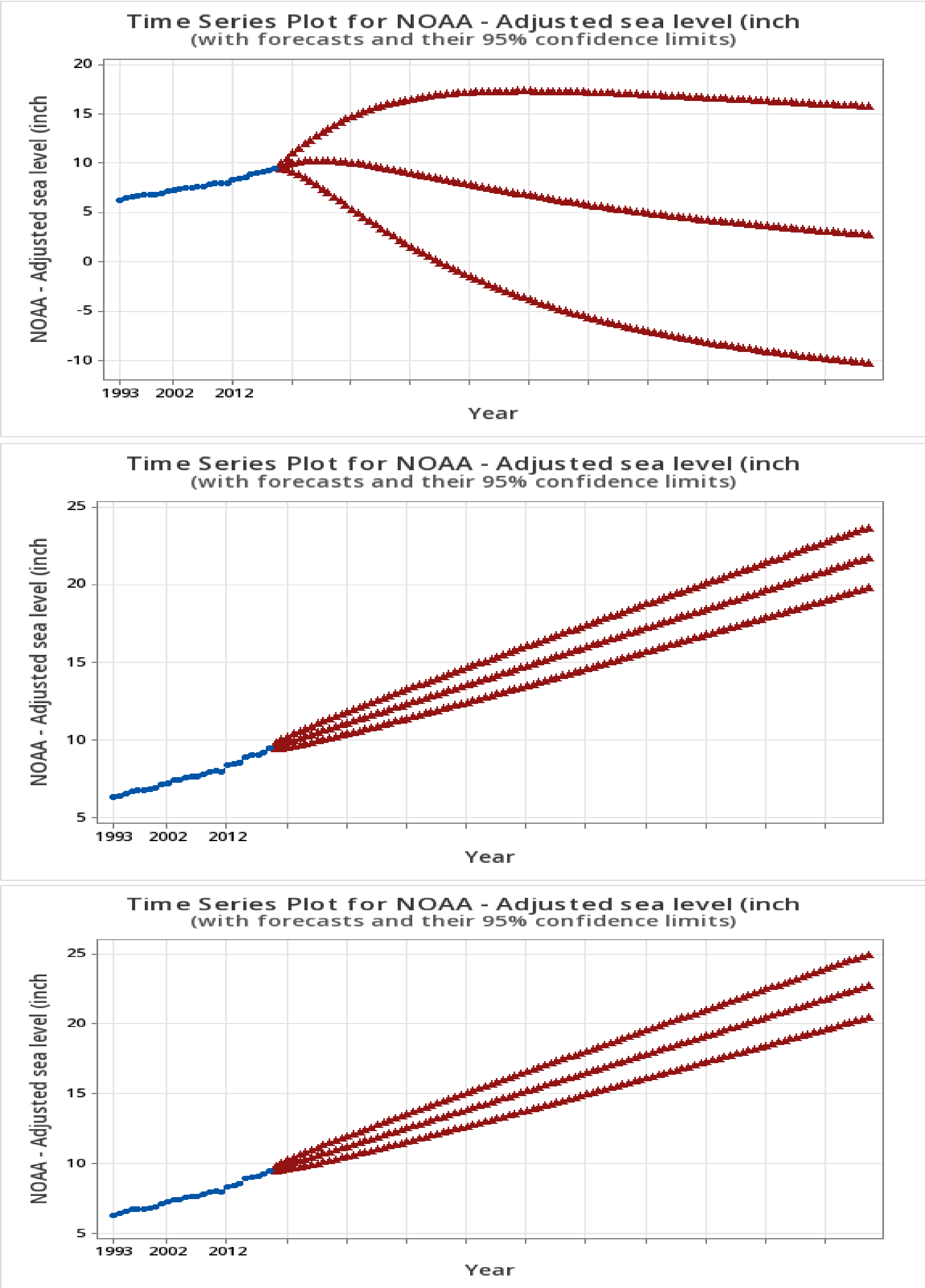

Figure 6. Holistic view of the trend showing forecasting at d =0, 1 and 2 in their respective order from top to bottom graph

Collectively, Figure 6 illustrates the impact of the differencing order (d) on the model's ability to fit the historical data and generate forecasts. The distinct forecast patterns underscore the importance of appropriate model selection. The d=1 and d=2 models appear to capture the general upward trend in sea level, while the d=0 model's forecast raises concerns. It's crucial to remember that these forecasts are based on the adjusted sea level data. The long-term trend component, removed during the adjustment process, is not explicitly modeled here but is essential for a complete understanding of future sea level change (Frederikse et al., 2020).

The sea level data was adjusted based on the NOAA CSV database, which provides crucial context. This adjustment typically refers to the removal of certain influences from the raw sea level measurements to isolate the signal of interest. Common adjustments include Glacial Isostatic Adjustment (GIA), which accounts for the ongoing vertical movement of the Earth's crust in response to the melting of ice sheets since the last glacial maximum. This movement can affect local sea level measurements and needs to be corrected for when studying long-term sea level rise (NOAA, 2022). Vertical land motion (VLM) corrections are also applied to isolate the absolute sea level change, accounting for local land subsidence or uplift due to factors like groundwater extraction, tectonic activity, or sediment compaction (NOAA, 2022). Depending on the specific NOAA dataset and the research goals, other adjustments might be applied, such as corrections for atmospheric pressure, wind effects, or tidal variations (NOAA, 2022).

The fact that a random walk model fits well suggests that the interannual fluctuations are essentially "noise" – random variations around the long-term trend. This could be due to a combination of factors, such as short-term climate variability (e.g., El Niño-Southern Oscillation), localized and transient oceanographic effects, and remaining measurement errors or uncertainties in the adjustment process (Lobeto & Menendez, 2024). Even if the interannual variability is unpredictable, it is still relevant for coastal management. Coastal communities need to be resilient to these fluctuations, even if they cannot be precisely forecast (Dangendorf et al., 2024). By focusing on the residual variability and clearly explaining the data adjustment process, meaningful research can be generated from the analysis, even if the "best" model is a simple random walk.

A 100-year forecast from the ARIMA(0,1,0) model, while bound by adjusted sea level and its interannual variability, delivers several important aspects. interannual uncertainty is quantified, as year-to-year fluctuations in sea level remain relevant for coastal communities. A quantitative estimate of the magnitude of these interannual variations is provided by the forecast and its confidence intervals. Use of this information can be made in coastal planning to assess the risk of temporary high-water events, such as storm surges superimposed on high tides, and plans can be made accordingly (Sweet et al., 2022). In infrastructure design, the range of potential interannual sea level fluctuations can be incorporated by engineers into the design of coastal infrastructure, including bridges, roads, and buildings (Nicholls et al., 2014). For emergency preparedness, the forecast can be used by emergency managers to prepare for potential coastal flooding events, even if precise timing and magnitude cannot be predicted. Furthermore, the random walk model serves as a useful baseline against which more complex sea level models can be compared. If a more sophisticated model, perhaps one including external climate variables or non-linear dynamics, cannot significantly outperform the random walk model in forecasting accuracy, its added complexity might not be justified. Evidence is provided by the analysis that, at least within the ARIMA family, simpler is better for this specific adjusted dataset, aligning with the principle of parsimony in model selection (Burnham & Anderson, 2002). The critical importance of accurately estimating and projecting the long-term trend itself is indirectly emphasized by this work, which focuses on the variability around such a trend. As the long-term trend dominates overall sea level rise, the need for separate research efforts dedicated to understanding and modeling these trends is highlighted (Church & White, 2011). Data quality assessment is also possible, as the strong performance of a simple random walk model on the adjusted data could indicate that adjustments, like GIA and VLM, were effective in removing long-term trends and other predictable components (Peltier, 2004; Wöppelmann & Marcos, 2016). Conversely, the necessity of more complex models might suggest that some predictable long-term signals remained in the data, even post-adjustment. Regional insights, with caveats, can be gleaned, as the analysis, though based on potentially regional NOAA data, can provide some insights into the specific characteristics of sea level variability in that region. Nevertheless, limitations of the random walk model, particularly its inability to capture long-term trends and its reliance on the assumption that future variability will resemble past variability, should be acknowledged. For a more complete picture of future sea level change, the analysis of variability should be combined with independent estimates of long-term sea level trends for the region of interest (Frederikse et al., 2020). Further research into exploring more complex models or to investigate the specific factors driving interannual sea level fluctuations in the region is suggested.

It is crucial to acknowledge the scope boundary in this analysis. The use of annual resolution data is a limitation that precludes the analysis of seasonal or event-scale variability, which is critical for many coastal applications. Future work should employ higher-frequency data to address these shorter timescales. Firstly, the forecasts pertain specifically to adjusted sea level, meaning the long-term trend has been removed. Therefore, the forecasts do not represent a total sea level rise, which includes both the long-term trend and the short-term fluctuations. Secondly, screening for ARIMA models, including the random walk model, relies on the assumption that the statistical relationships observed in the past will continue into the future. This assumption may not hold true, especially over long forecast horizons like 100 years, as factors influencing sea level variability may change. Thirdly, while the Minitab tool automates model selection, it is essential to critically evaluate the selected model's diagnostics (e.g., residual analysis) to ensure its adequacy (Box et al., 2015). Finally, the reliance on a single statistical model does not preclude the possibility that other models, potentially outside the ARIMA family, may provide superior forecasts. Despite these limitations, this research provides valuable insights into the interannual variability of adjusted sea level, offering crucial information for coastal planning and management. Furthermore, the 100-year forecast horizon is an illustrative projection of the model's behavior. Given the limited historical data and the assumption that past statistical properties hold constant, forecasts this far into the future are highly uncertain and should be interpreted with caution. The primary value is in quantifying the increasing uncertainty, not the precise point forecast.

CONCLUSION

The ARIMA(0,1,0) model, selected after an extensive screening of the ARIMA parameter space, represents the best ARIMA representation of the adjusted sea level data, implying that the residual interannual variability, after accounting for factors removed during data adjustment, is largely unpredictable within the ARIMA framework. This result underscores the critical need for separate research focused on modeling long-term sea level trends, which are not captured by this analysis. Future research should therefore move beyond the ARIMA framework to explore non-linear time series models or models directly incorporating climate indices (e.g., ENSO, NAO) as predictors to attribute causality and improve predictive skill. While the possibility of superior models outside the ARIMA family, such as non-linear time series models or models incorporating climate indices like the ENSO index, remains open and warrants further investigation, the random walk's selection reinforces its role as a relevant baseline. This research highlights the importance of distinguishing between short-term variability and long-term trends in sea level studies. Although the forecast does not directly predict total future sea level, it provides valuable information about the unpredictable interannual fluctuations superimposed on the long-term trend, which is crucial for coastal planning, infrastructure design and emergency preparedness. It is important to note that these forecasts represent only the unpredictable residual component and must be integrated with independent projections of the long-term trend and event-based hazard models for practical, localized decision-making. Given the importance of data adjustment, future work should conduct a sensitivity analysis to assess the impact of different GIA and VLM correction methods on the results of the ARIMA modeling. This would help to quantify the uncertainty associated with the adjustment process and its influence on the conclusions about interannual sea level variability. Moreover, further research studies could investigate the influence of specific climate forcings (e.g., greenhouse gas concentrations, volcanic eruptions) on long-term sea level trends using regression models or more complex climate models. This would help to better understand the drivers of long-term sea level change and improve projections. This adds a layer of causal understanding to trend estimation.

Compliance with Ethical Standards

Conflict of Interest

The author declares that there is no conflict of interest.

Ethical Approval

For this type of study, formal consent is not required.

Funding

Not applicable.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

AI Disclosure

Generative AI was used for grammatical and language review of the introduction and discussion sections. The author validated all outputs and assume full responsibility for the content.

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Comparison of the Fit of the Richards Model to Broiler Chicken Growth Data With Gompertz and Logistic Models

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ABSTRACT

This study comparatively evaluates three nonlinear regression models (Richards, Gompertz, and Logistic) commonly used to mathematically model the growth process of commercial broilers. The primary objective of the study was to determine the model that most accurately represents the growth curve by analyzing the fit of these models to live weight data. In the study, 360 Ross 308 hybrid male broiler chicks were monitored until 50 days of age, and weekly live weight measurements were taken. Parameter estimates for each model were evaluated based on statistical fit metrics, including root mean square error (RMSE), coefficient of determination (R^2), Akaike Information Criterion (AIC), and Bayesian Information Criterion (BIC). The results showed that the Richards model showed the highest fit across all criteria. The Gompertz model ranked second, and the Logistic model ranked third. However, all three models demonstrated high performance in explaining the growth process of broilers. These results highlight the importance of growth modeling as a key decision-support tool for determining optimal slaughter timing and feeding strategies, particularly in broiler production. The flexible structure of the Richards model makes it the most desirable option in terms of biological significance and statistical relevance.

INTRODUCTION

Broiler farming is a significant livestock activity at both the global and national levels due to its advantages, including high yields at low costs and the ability to quickly market products (Topal & Bölükbaşı, 2008; İzgi et al., 2020). Accurately monitoring live weight gain during the production process and determining the ideal slaughter time are crucial for both economic efficiency and resource utilization (Bilgin & Esenbuğa, 2003). Therefore, expressing growth curves using mathematical models is becoming an important tool to support breeder decisions (Aggrey, 2002; Adamu et al., 2021).

Growth curve models are used to predict changes in live weight of animals with age and are divided into two basic groups: Linear and nonlinear models (Efe, 1990). Nonlinear models are more widely preferred in animal husbandry because they better reflect biological reality (Masoudi & Azarfar, 2017). The Richards, Gompertz, and Logistic models are among the most frequently used nonlinear models to describe growth curves in broiler chickens. However, the predictive success of these models can vary depending on the data set used and application conditions (Söğüt et al., 2005; Michalczuk et al., 2016; Falana et al., 2024).

Recent studies emphasize the importance of model selection based on growth dynamics and biological interpretation. Ghavi Hossein-Zadeh (2025) investigated alternative nonlinear models in partridges, while Xie et al. (2020) compared nonlinear models for feather growth in yellow-feathered chickens, examining variation in model performance across traits and genotypes. Similarly, Kucukonder et al. (2020) and Falana et al. (2024) evaluated model fit in broilers, demonstrating how predictive accuracy and biological realism can vary.

Despite these advances, updated evaluations of the Richards model using robust statistical criteria are needed in modern commercial broiler breeds. The novelty of this study lies in the comprehensive comparison of three key nonlinear models (Richards, Gompertz, and Logistic) based on goodness-of-fit metrics (RMSE, AIC, BIC) and biological interpretation of the parameters.

This study aims to evaluate the performance of the Richards model in explaining the growth curve of commercial broiler chickens in comparison with the Gompertz and Logistic models, and to provide recommendations based on statistical criteria for model selection.

MATERIAL AND METHODS

Animal Material

The study was conducted at the Atatürk University Food and Livestock Application and Research Center. All the experimental protocols adhered to and were approved by the guidelines of the Animal Ethics Committee of Ataturk University (Approval date: 25 December 2009; Decision No: 09/123). A total of 360 one-day-old Ross-308 hybrid male broiler chicks were used in the study. Initial weights of the chicks were determined and recorded individually on the day they were brought to the experimental area. During the 50-day trial, the chicks were provided with two different commercial feeds formulated for their growth stages (starter and grower). Feed and water were provided with free access to the birds. Environmental conditions within the coop, including temperature, humidity, and ventilation, were optimized by commercial broiler standards. The lighting program was applied continuously 24 hours a day for the first three days and continued periodically on subsequent days.

In the study, starter (broiler) and grower (broiler) feeds with two different nutrient compositions were obtained from a commercial feed factory. The composition of the compound feeds given to the animals in the trial, their feed ingredients, and their nutrient compositions are presented in Table 1.

Table 1. Nutrient composition of the feeds

Nutrient Composition	Broiler Starter Feed	Broiler Grower Feed
Moisture (%)	12.00	12.00
Crude protein (%)	22.00	20.00
Crude fiber (%)	7.00	7.00
Crude ash (%)	8.00	8.00
Ash insoluble in HCl (%)	1.00	1.00
Metabolizable energy (kcal/kg)	3000 kcal/kg	3100 kcal/kg
NaCl	0.35	0.35
Lysine	1.20	1.00
Methionine	0.50	0.40
Cystine	0.40	0.35
Calcium (Ca)	0.60-1.50	0.60-1.50
Phosphorus (P)	0.60	0.60
Sodium (Na)	0.10-0.30	0.10-3.00

Data Collection

The live weights of the chicks were measured weekly; on the 8th, 15th, 22nd, 29th, 36th, 43rd, and 50th days, it was measured and recorded separately for each individual using scales with milligram precision.

Growth Models

In this study, three different nonlinear growth models were used to describe the growth curve of broiler chickens. These models are:

$$Richards: Y_t = A[1+\beta\ exp^{-kmt}]^{-1/m} \quad (1)$$

$$Gompertz: Y_t = A\ exp[-\beta\ exp^{-kt}] \quad (2)$$

$$Logistic: Y_t = A[1+\beta\ exp^{-kt}]^{-1} \quad (3)$$

In these formulations, Y_t represents the live weight at time t; A represents the asymptotic weight (final size); k represents the growth rate; m and β represent the parameters that define the shape of the growth curve.

The coefficient A in nonlinear models represents the asymptotic limit of measurement that the animal can reach. This asymptotic value represents the highest measurement level that the animal can achieve, regardless of short-term changes in body size, which generally occur due to pregnancy, lactation, and environmental factors. This parameter, 'A', which defines adult body size, can be estimated by all growth curve models and is expressed in the appropriate unit depending on the measured trait. The body measurement value of an animal recorded at age t months can theoretically never exceed the parameter A (Şahin et al., 2014). Among the constants in nonlinear models, A is the most easily interpreted from a biological perspective and deserves special attention (Şireli & Ertuğrul, 2004).

The parameter β, which varies according to the initial value, is defined as the ratio of postnatal growth to the adult body size. The "±" sign in the model depends on the value of the parameter m, which represents the exponential power. Accordingly, β is negative when $m > 1$ and positive when $m < 0$ (Akbaş, 1995).

The k parameter in the model is a function representing the maturation rate. This rate varies depending on the A (adult body size) and m (curve shape) parameters in the model. A high k value indicates rapid development, while a low k value indicates a slower developmental process (Brown et al., 1976).

Estimates of the A, β, k, and m parameters obtained from nonlinear models are calculated using the generalized least squares method and the Levenberg–Marquardt iterative algorithm (Draper & Smith, 1981; Akbaş et al., 1999).

Data Analysis

Each model was compared using statistical fit metrics such as the coefficient of determination (R^2), root mean square error (RMSE), Akaike Information Criterion (AIC), and Bayesian Information Criterion (BIC). The Root Mean Square Error (RMSE), used for this purpose, represents the square root of the mean square of the difference between the model's predicted values and the actual observed values. A smaller value indicates a higher predictive accuracy of the model. The Akaike Information Criterion (AIC) and the Bayesian Information Criterion (BIC) jointly assess both how well the model fits the data and how simple it is in terms of the number of parameters it has. AIC imposes a relatively weaker penalty for model complexity, while BIC imposes a more stringent penalty. Lower values for both criteria indicate a more suitable and balanced model. Model fit was assessed based on the highest R^2 value and the lowest RMSE, AIC, and BIC values. Collected live weight data were analyzed using the SPSS 25.0 statistical package.

RESULTS

This study compared the performance of the Richards, Gompertz, and Logistic models to model the 50-day growth process of commercial broiler chickens. All three models are nonlinear and widely used in the literature to describe the biologically sigmoidal shape of the growth curve. The models were examined in detail for predictive accuracy using estimated parameters and fit metrics. The key parameters and standard errors estimated by all three models for the growth curve are presented in Table 2.

Table 2. Estimated parameter values for broiler chickens using nonlinear growth models

Model	A	β	k	m
Richards	3337.89±112.78	-7.986±2.56	0.079±0.0065	-1.868±0.98
Gompertz	4371.47±83.19	5.144±0.031	0.046±0.0087	—
Logistic	3024.24±29.61	40.536±0.53	0.108±0.00068	—

Table 3. RMSE, R^2, AIC, and BIC values calculated with nonlinear growth models

Model	R^2	RMSE	AIC	BIC
Richards	0.999	1711.75	30.44	26.05
Gompertz	0.998	2249.28	30.03	26.74
Logistic	0.998	2021.51	30.26	26.97

The Richards model predicts a moderate adult body weight with an estimate of 3337.89 ± 112.78 g for the asymptotic weight (*A*) parameter, which is found to be in good agreement with the final slaughter weights observed in broilers. The Gompertz model, on the other hand, provides the highest *A* estimate of 4371.47 ± 83.19 g, while the Logistic model provides the lowest value of 3024.24 ± 29.61 g (Table 2). This suggests that the Gompertz model tends to overestimate the later stages of the growth process, while the Logistic model assumes a symmetric growth process that reaches saturation early. Topal & Bölükbaşı (2008) reported that the Gompertz and Logistic models yielded similarly high and low predictions in asymptotic weight estimates. Furthermore, Knížetová et al. (1991), Ersöz & Alpan (1994), emphasized that the Richards model provided predictions closest to biological reality. Recent studies have confirmed these observations, showing that the Richards model offers a flexible and biologically realistic structure for growth modeling in poultry (Kucukonder et al., 2020; Falana et al., 2024; Ghavi Hossein-Zadeh, 2025).

The β value, one of the parameters that directs the curve shapes of the models, is negative at –7.986 ± 2.56 in the Richards model. This is due to the m parameter also being negative (–1.868 ± 0.98). This value indicates that the growth curve is asymmetric, meaning that growth is slow in the early stages and faster in the middle and late stages (Table 2). This structure is quite consistent with the growth biology of commercial broilers. Similarly, Şireli & Ertuğrul (2004) and Akbaş (1995) stated that the m parameter is a biologically meaningful indicator in describing the asymmetry in the growth curve. Because the m parameter is not included in the Gompertz and Logistic models, these models are limited by the assumption of symmetric growth. This limitation of the Logistic model has also been emphasized in recent literature (Xie et al., 2020; Adamu et al., 2021). The *β* value was found to be more stable at 5.144 ± 0.031 in the Gompertz model, while it was significantly higher at 40.536 ± 0.53 in the Logistic model. This supports the Logistic model's prediction of a very rapid increase at the beginning of growth.

For the parameter k, representing the growth rate, the highest value was obtained in the Logistic model (0.108 ± 0.00068), while the lowest value was obtained in the Gompertz model (0.046 ± 0.00087). The Richards model lies between these two extreme values (0.079 ± 0.0065) and assumes a more balanced growth process. A high *k* value suggests that the Logistic model predicts rapid maturation, while a low *k* value suggests that the Gompertz model describes a slower developmental process (Table 2). This differentiation in maturation speed predictions among models was also demonstrated by Falana et al. (2024) and Kucukonder et al. (2020), who found that Gompertz and Richards provide more biologically plausible maturation trajectories than Logistic.

Considering the obtained parameter estimates and standard errors, the Richards model appears to be the most biologically appropriate model, both because it has the m parameter, which provides curve flexibility, and because it reflects asymptotic and interim values more consistently. The Gompertz model stands out as a highly reliable alternative, particularly with its low standard errors and biologically meaningful parameter structure. However, the Logistic model has limited utility in long-term growth prediction due to its early saturation assumption. This has been corroborated by Xie et al. (2020), who noted that the Logistic model underrepresents late-stage growth in poultry, and by Ghavi Hossein-Zadeh (2025), who found Richards to outperform Logistic in similar avian species. These findings are consistent with previous studies supporting the Richards model's preference in broiler growth modeling (Ersöz & Alpan, 1994; Knížetová et al., 1991; Topal & Bölükbaşı, 2008). The fit of the models to the growth data was evaluated using various statistical criteria, and the results are presented in Table 3.

In this study, the statistical fit performances of Richards, Gompertz, and Logistic models applied to live weight data of broiler chickens were compared using basic fit metrics such as coefficient of determination (R^2), root mean squared error (RMSE), Akaike (AIC), and Bayesian (BIC) information criteria. According to the results, the Richards model demonstrated the best fit across all criteria. This model offers the highest explanatory power for growth data with $R^2 = 0.999$, while also offering the lowest errors and the highest model parsimony with RMSE = 1711.75, AIC = 30.44, and BIC = 26.05. This finding stems from the m parameter, which allows the Richards model to represent the early, middle, and late stages of the growth process with a more flexible structure. Indeed, Knížetová et al. (1991), Ersöz & Alpan (1994), and Xie et al. (2020) also reported that the Richards model provided high fit in free-feeding chickens and broilers.

The Gompertz model demonstrated a statistically strong fit with a relatively high $R^2 = 0.998$. However, the RMSE = 2249.28 reveals that it exhibits greater deviations from observed values compared to the Richards model. Notably, while the AIC (30.03) and BIC (26.74) values for the Gompertz model appear slightly lower than those for the Richards model, this difference is minimal, and in practice, the model lags behind the Richards model in terms of explanatory power and predictive accuracy. This model's tendency to overestimate asymptotic weight and its symmetrical curve structure may lead to increased prediction errors, especially in late growth stages. However, studies such as Topal & Bölükbaşı (2008) and Aggrey (2002) also indicated that the Gompertz model demonstrated successful fit in broilers, providing highly reliable predictions, particularly in the middle stages of growth. Similarly, Adamu et al. (2021) and Falana et al. (2024) reported that the Gompertz model offered biologically meaningful and statistically acceptable results in broiler growth modeling under commercial conditions.

The logistic model, however, lagged behind the other two models in terms of overall fit. Although the coefficient of determination (R^2) = 0.998 appears high, the values of RMSE = 2021.51, AIC = 30.26, and BIC = 26.97 indicate that the model does not accurately reflect the observed values, particularly in the later stages of the growth curve. The hypothetical symmetrical structure of the logistic model, which tends to saturate early, does not fully reflect the rapid growth characteristics of broilers in the late growth period. Yakupoğlu & Atil (2001) similarly reported that this model has limited application and is particularly inadequate in asymmetric growth processes. Kucukonder et al. (2020) and Xie et al. (2020) also emphasized the limitations of the Logistic model in describing asymmetrical growth in broilers and yellow-feathered chickens.

Overall, all three models successfully predicted the general shape of the broiler chicken growth curve. However, a closer look at the different stages of the growth process revealed that the Richards model showed the highest degree of agreement with observed values, particularly in the middle and late stages. While the Gompertz model performed reasonably well in the mid-term predictions, the Logistic model's accuracy was limited due to its early plateauing structure. Ghavi Hossein-Zadeh (2025) similarly found that flexible models like Richards provided superior predictions for asymmetric growth patterns in partridges, further supporting its applicability in poultry species. These results demonstrate that the Richards model is the most suitable growth model in terms of both biological consistency and statistical adequacy, while the Gompertz model is a reliable and rapidly applicable alternative.

Table 4 presents a comparison of the observed live weights of commercial broiler chickens with the values predicted using the Richards, Gompertz, and Logistic models. Based on this data, the success rates of the models at different stages of the growth process were analyzed and plotted in Figure 1. In the early growth period (days 0 and 8), the Logistic model produced significantly higher estimates than observed values. In contrast, the Gompertz model provided lower initial estimates, while the Richards model provided relatively more stable but slightly higher estimates. This suggests that the Richards model, in particular, reflects biological reality more accurately than the initial conditions. When analyzing the middle period (days 15–36), all models generally fit the curve form, but the Richards model's estimates were closest to the observed values. This indicates that the Richards model yielded the lowest deviation in this stage. In the late period (43–50 days), the Richards and Logistic models' predictions were very close to the observed values, while the Gompertz model's prediction at day 50 was overestimated. This suggests that the Gompertz model may be overly biased in predicting asymptotic magnitude. The Logistic model, on the other hand, provided closer predictions in the late period but fell short in overall curve fit (especially at the beginning).

Our findings are consistent with previous studies reporting the successful application of the Richards and Gompertz models in broiler chickens (Topal & Bölükbaşı, 2008). Our study contributes to the literature by re-evaluating these models in terms of both theoretical fit and practical predictive power.

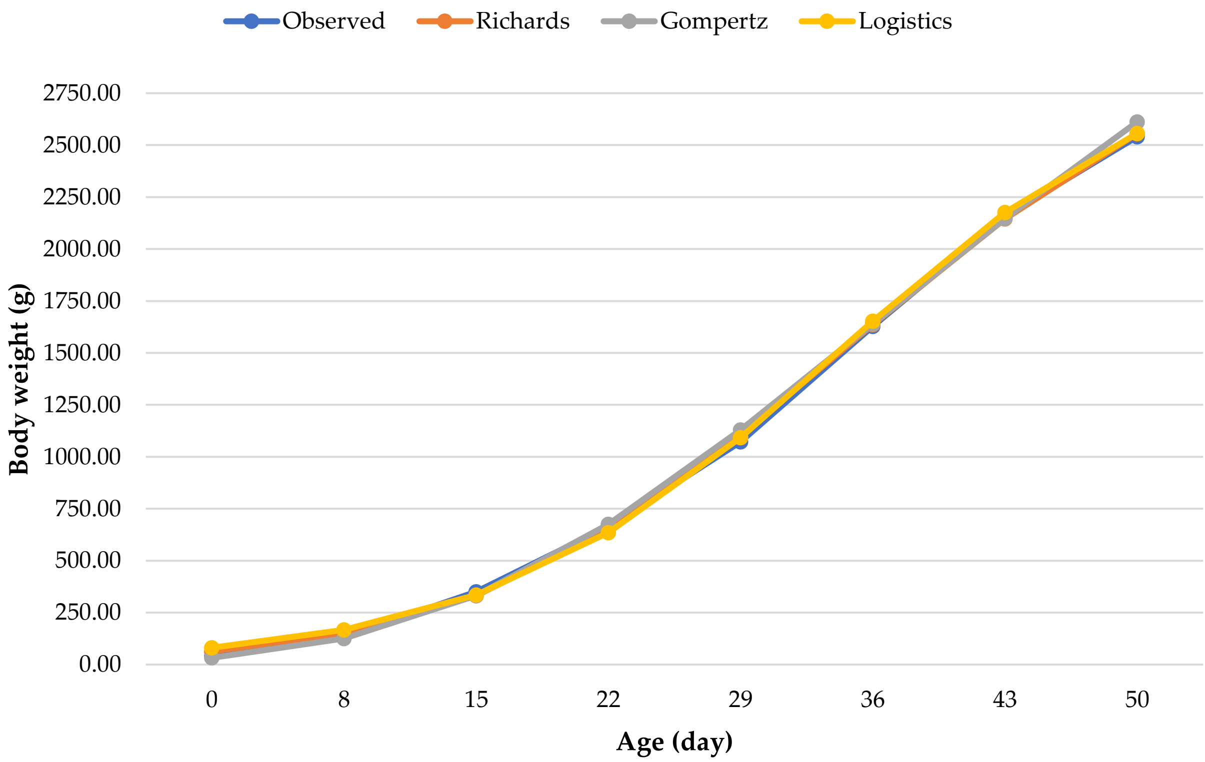

Figure 1. Growth curves estimated with nonlinear models for broilers

Table 4. Live weight values (g) for commercial broiler chickens, observed and predicted by nonlinear growth models

Day	Observed	Richards	Gompertz	Logistic
0	41.14	62.94	32.26	80.88
8	133.12	151.02	124.63	167.21
15	350.06	331.73	331.87	335.18
22	664.52	648.21	674.86	634.41
29	1072.02	1104.25	1128.75	1092.27
36	1627.25	1636.21	1638.64	1652.13
43	2156.71	2144.28	2146.85	2175.77
50	2540.31	2555.26	2611.09	2556.20

DISCUSSION

The evaluations demonstrate that the Richards model most accurately reflects the growth curve of commercial broiler chickens. Both the parameter estimates and the goodness-of-fit statistics ($R^2 = 0.999$, RMSE = 1711.75) confirmed the superior performance of the Richards model compared to Gompertz and Logistic models. Analyses of the data in this study reveal that the Richards model distinguishes itself from other models with its flexible parameter estimates and superior fit criteria. In particular, the ability of the "m" parameter to manipulate the shape of the curve allows it to capture the different rates of growth in early and late stages more effectively than other models. This conclusion is consistent with studies by Ersöz & Alpan (1994), Knížetová et al. (1991), and Falana et al. (2024). These studies also stated that the Richards model should be preferred for broiler growth modeling in terms of both biological significance and statistical relevance. Additionally, the Richards model provided the closest predictions to the observed data throughout all growth phases, especially from day 15 onwards, where it maintained minimal deviation from observed values.

The Gompertz model was also found to successfully represent the growth curve, yielding results similar to the Richards model. It yielded predictions consistent with the observed data, particularly in the middle stages of growth. However, it was observed that it failed to represent the asymptotic portion of the curve as well as the Richards model in later periods. Despite having strong statistical performance ($R^2 = 0.998$, RMSE = 2249.28), it tended to overestimate body weight during the final growth stage (day 50). However, the Gompertz model stands out as a valid alternative because it has biologically meaningful parameters and reflects the fundamental characteristics of growth. Indeed, Topal & Bölükbaşı (2008) reported that the Richards and Gompertz models performed well in broiler chickens and are generally the top two preferred models. More recent findings, such as those by Kucukonder et al. (2020), Adamu et al. (2021), and Falana et al. (2024), support this view by highlighting the Gompertz model's practical applicability despite its limitations in late-stage prediction.

The logistic model, however, was found to perform less well than the other two models. It was observed that the logistic model reached a saturation point earlier in the growth curve and did not fully conform to the long-term growth trend observed in broiler chickens. This premature plateau effect, evident from the early overestimations (0st and 8th day), caused reduced predictive accuracy in both early and late stages. This could lead to greater deviations in the prediction of observed values, especially at later ages. As stated in the literature, the assumption that the growth curve of the Logistic model is symmetrical causes it to fail to adequately represent the asymmetric growth process in broiler chickens (Yakupoğlu & Atil, 2001; Xie et al., 2020; Kucukonder et al., 2020; Adamu et al., 2021; Falana et al., 2024). Furthermore, the Logistic model yielded a relatively higher RMSE (2021.51) despite similar R^2 values, indicating a less precise fit.

The results of the present study emphasize the importance of selecting models that balance biological realism and statistical relevance when modeling growth in broiler chickens. In this context, the Richards model stands out as the most suitable model, thanks to its ability to precisely monitor the different growth stages, particularly in commercial farming. The Gompertz model also follows the Richards model, offering acceptable accuracy and biological relevance. The logistic model, however, lags behind other models due to its limited predictive capacity. This is particularly critical for applications in commercial production, where accurate modeling supports decisions related to feed planning feeding, market timing, and cost optimization.

CONCLUSION

In this study, the objective was to comparatively evaluate the fitting performances of three different nonlinear models (Richards, Gompertz, and Logistic) to growth curves in broiler chickens. The findings indicate that the Richards model, thanks to its flexible structure, provides the closest estimates to the observed weight values across all growth periods and is therefore the most suitable model in terms of both biological significance and statistical reliability. The "*m*" parameter in the model is indicative of the asymmetric structure of the growth curve, with greater accuracy in the representation of the early and late stages of growth. The Gompertz model is regarded as a favorable option in practice due to its ease of implementation and successful predictions in certain growth periods. However, it should be used with caution due to its tendency to overestimate weight in adult stages. Conversely, the logistic model is predicated on the assumption of symmetrical growth, a premise that is therefore incapable of fully reflecting the asymmetric growth structure of broilers. Consequently, its efficacy in predicting long-term growth appears to be constrained.

In conclusion, the present study demonstrates the potential of the Richards model to function as an effective decision-support tool for a number of purposes, including the monitoring of growth, the planning of feeding programs, the determination of slaughter times, and the optimization of production strategies in the context of commercial broiler production. The utilization of this model within the industry, as evidenced by extant empirical data, has the potential to engender substantial contributions to both scientific and economic domains. Subsequent analyses, encompassing diverse genotypes, rearing conditions, and sex groups, have the potential to further expand the model's validity and application.

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Compliance with Ethical Standards

Authors' Contributions

ST: Conceptualization, Investigation, Methodology, Formal Analysis, Writing – original draft, Writing – review & editing

NE: Conceptualization, Supervision, Writing – review & editing

All authors read and approved the final manuscript.

Conflict of Interest

The authors declare that there is no conflict of interest.

Ethical Approval

For this type of study, formal consent is not required.

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Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

AI Disclosure

The authors confirm that no AI was used in the writing of this article or in the presentation of images, tables or information.

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Multi-Level Analysis of Wheat Import Sensitivity in IGAD Countries: From Country-Level Elasticities to Regional Causal Dynamics

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ABSTRACT

This paper explores how wheat import volumes in Intergovernmental Authority on Development (IGAD) countries respond to global price changes, and whether these reactions vary across countries or over time. Wheat is a critical staple in the region, and its import dynamics are increasingly important as the bloc faces recurring shocks like drought, conflict, and global price spikes. Using a two-pronged approach, we first apply country-level autoregressive distributed lag (ARDL) models and find long-run cointegration across all IGAD members. Eritrea and Ethiopia show strong long-run negative price elasticities, pointing to substitution or price-sensitive behavior. South Sudan, Sudan, and Somalia display short-run positive responses, likely linked to urgent procurement or aid-related deliveries. Uganda shows limited responsiveness, while Djibouti—though also reactive in the short term—likely reflects its role as a re-export hub rather than fragility-driven volatility. Kenya shows both long-run sensitivity and short-run spikes, indicating a more complex market and policy mix. At the bloc level, panel Granger causality tests reveal a two-way relationship between global wheat prices and imports. Notably, imports also Granger-cause price shifts—an unexpected result suggesting that even uncoordinated regional import behavior may shape market expectations. This finding strengthens the case for more strategic procurement and regional storage mechanisms.

INTRODUCTION

Wheat is a vital component of the global food supply, particularly in regions with limited domestic production and high reliance on international markets (FAO, 2022a). The Intergovernmental Authority on Development (IGAD) region, comprising eight East African nations—Djibouti, Eritrea, Ethiopia, Kenya, Somalia, South Sudan, Sudan, and Uganda—is one such area, characterized by significant fragility and food insecurity (IGAD, 2025). With a population exceeding 320 million (World Bank, 2025), most IGAD countries heavily depend on wheat imports to fulfill domestic demand, a reliance intensified by ongoing droughts, civil wars, economic challenges, and constrained agricultural capacity.

This pronounced fragility heightens its susceptibility to global wheat price fluctuations. Events such as the 2007–2008 food crisis, the 2022 price surge driven by the Russia–Ukraine conflict, and recent climate-induced production disruptions underscore the vulnerability of these fragile economies to external price shocks. Despite this structural exposure, the empirical literature has largely neglected the IGAD region, particularly regarding wheat import patterns and their sensitivity to global price trends.

This study fills the research gap by performing a multi-level analysis of wheat import sensitivity in IGAD member states. It examines how these countries, both individually and as a group, react to global wheat price volatility over time and explores whether their import behavior generates feedback effects that might shape market expectations. Understanding these dynamics is crucial for academic research and for guiding regional policy, particularly as IGAD nations pursue enhanced economic cooperation amid recurring supply chain challenges.

We frame the analysis around the following core research questions:

- How do IGAD countries differ in their responsiveness to global wheat price changes?
- Are these responses observed in the short run, the long run, or both?
- Does the bloc exhibit collective import behavior that contributes to or reacts to global price dynamics?
- What do these empirical patterns imply for regional procurement, storage strategies, and food security policy?

To investigate these issues, we employ a dual econometric approach. At the country level, we utilize autoregressive distributed lag (ARDL) models, as developed by Pesaran et al. (2001), to evaluate both short-run and long-run price elasticities of wheat imports. This method accounts for each country's distinct institutional, economic, and climatic conditions, enabling a tailored analysis of import behavior. At the regional level, we apply panel Granger causality tests, as proposed by Juodis et al. (2021), to examine whether IGAD's collective import volumes respond to global price fluctuations and, intriguingly, whether they also exert influence on those prices.

This study offers three key contributions to the literature. First, it brings the IGAD bloc into the discourse on wheat price volatility through a robust empirical approach, addressing a critical geographic and thematic gap. Second, it combines micro-level (country-specific) and macro-level (bloc-wide) econometric methods, providing a pioneering multi-scale framework for analyzing commodity import sensitivity. Third, it delivers actionable insights for policymakers: the finding that IGAD imports Granger-cause global price shifts, even without a coordinated procurement strategy, indicates the bloc's latent market influence. Leveraging this through joint procurement mechanisms, shared storage infrastructure, and improved import planning could bolster food security and mitigate price vulnerability across the region.

Wheat Export (Supply), Import (Demand) and Price Cycle: General Mechanics

Wheat is a fundamental global commodity. It is not just like any tradable item, but a critical component of global food security. Its versatile nature makes it so important that disruptions in its export (supply) or major shifts in its price can have severe implications for countries that depend on it. This importance is notable in the global consumption trend. In just under a decade worldwide import (demand) rose from 161.9 million tons in 2014 to 211.3 million tons in 2023, an increase of over 30% as Shown in Figure 1.

Export (supply) volumes followed a similar trend, with periodic downturns caused by demand shocks and supply disruptions as shown in Figure 2.

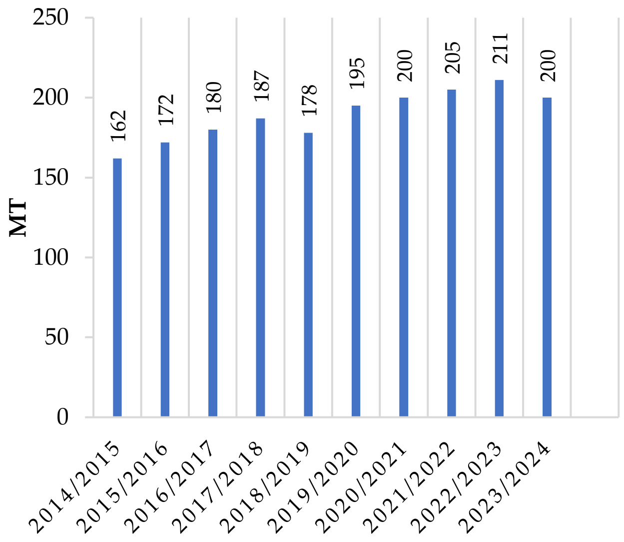

Figure 1. Global wheat demand (import) volume (Source: Statista, 2024a)

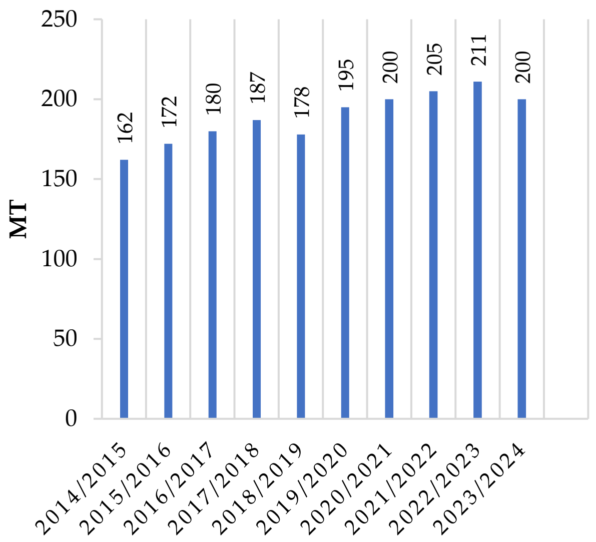

Figure 2. Global wheat supply (export) volume (Source: Statista, 2024b)

Global wheat price dynamics are shaped by interacting supply and demand factors. On the supply side, weather extremes, input costs, geopolitical tensions, and chokepoints like the Suez Canal create sudden shocks. On the demand side, wheat's staple status and government-driven procurement make adjustments slow. These structural pressures explain the sharp price swings observed in global markets.

Volatility Transmission: From Global Prices to Domestic Availability and Affordability

When global wheat prices spike, importing countries all face the same basic challenge: securing enough supply at an affordable cost. But they do not all cope equally. The transmission channel works through both affordability and availability.

Affordability refers to whether countries can pay for imports when prices rise. Many wheat-importing countries rely on foreign exchange reserves to finance these purchases. When global prices rise sharply, these countries must find additional foreign currency. This is especially hard for countries with floating exchange rates that tend to depreciate during crises. As their currencies weaken, the cost of wheat imports rises even more in local terms (IMF, 2022).

Availability is the other side of the problem. Even if a country can pay the higher price, there may simply not be enough wheat on the market to buy. Export bans, shipping disruptions, and competitive bidding from richer countries can limit physical supply. This dynamic was noticeable during the 2007–2008 and 2022 crises, when some exporters restricted shipments to protect local consumers, leaving importers scrambling to find supplies at any price.

Countries are not affecting equally and thus have different coping capacity.

- High-income, stable countries often have strong currencies and big reserves. They can navigate challenges fairly easily and even build up stocks during crises.
- Middle-income countries might use subsidies or tariff cuts to keep prices stable but often face budget constraints.
- Low-income and fragile states have limited fiscal capacity. They may be forced to reduce other essential imports to pay and prioritize this commodity or turn to donors and international agencies for emergency assistance (Headey & Fan, 2008).

Price Volatility in Import-Dependent Developing Countries and IGAD Bloc Particularity

The transmission mechanism applies to all import-dependent countries, regardless of region or income level, though capacity dramatically varies. However, the most exposed are the developing countries presenting the following factors:

- *Currency fragility*: Many developing countries have floating exchange rates and structurally weaker currencies. During global crises, investor confidence often drops, leading to currency depreciation. When this happens, the local cost of importing wheat rises even faster than the world price itself (IMF, 2022).
- *Limited fiscal space*: High-income countries can subsidize the commodity import or absorb higher costs without risking budget collapse. Developing countries often cannot. Subsidies strain public finances, and cuts elsewhere can lead to social tension.
- *High import dependence with little domestic substitution*: Many developing regions lack the climatic conditions or infrastructure to grow enough wheat locally. This dependency means they cannot quickly switch to other staples or local substitutes when prices rise.
- *Climate shocks* compound these problems. Many developing countries are in regions prone to drought, floods, and other extreme weather events. These reduce local food production just when imports become more expensive, deepening food insecurity (Wheeler & von Braun, 2013).
- Political instability is another factor. Conflicts, weak institutions, and poor governance can disrupt procurement, storage, and distribution. Even if wheat is imported successfully, getting it to consumers at stable prices can be difficult (World Bank, 2023).

The level of combination of these factors is a determinant element of the severity of the exposure to supply disruptions and price fluctuations. Given the structure of economic blocs in developing countries, the Intergovernmental Authority on Development (IGAD), in particular, stands out as a severely exposed bloc. It combines nearly all of these challenges in an extreme form, although there is a heterogeneity among country members.

- *Conflict and instability*: Somalia has experienced over 30 years of conflict. Sudan is currently going through a devastating civil war. South Sudan remains fragile since independence. Ethiopia had a devastating civil war from 2020 to 2022 that displaced millions (World Bank, 2023).
- *Protracted crises*: These conflicts are not one-off events but long-running, eroding institutions and social safety nets over decades.
- *Recurrent drought*: The Horn of Africa is among the world's most drought-prone regions. In recent years, multiple failed rainy seasons have caused massive food insecurity (FAO, 2022b).
- *Climate shocks*: Beyond drought, floods and locust invasions have further stressed food systems.
- *Currency fragility*: Except for Djibouti (which uses a USD-pegged currency), all IGAD countries have floating currencies that have depreciated significantly in recent years.
- *Weak fiscal capacity*: Limited ability to fund subsidies or strategic reserves.

This picture contrasts with other Regional Economics Communities (RECS) in the African continent or similar blocs elsewhere, where fragility exists but is usually not multi-dimensional or rarely comes all at once. Table 1 below illustrates the comparative fragility matrix pertaining to regional exposure to wheat import shocks.

IGAD Wheat Import Pattern and Trend

The Intergovernmental Authority on Development (IGAD) was established in 1996, as a successor to the Intergovernmental Authority on Drought and Development (IGADD), which was created in 1986 to address frequent droughts and food insecurity in the Horn of Africa. Today, IGAD includes eight countries: Djibouti, Eritrea, and Ethiopia, Kenya, and Somalia, South Sudan, Sudan, and Uganda— together home to more than 230 million people. Despite this shared platform, the region is marked by deep heterogeneity in terms of fragility to wheat import shocks as seen in Table 2.

Table 1. Comparative fragility matrix – regional blocs

Regional Bloc	Currency Fragility	Fiscal Space	Climate Shocks	Instability	Wheat Import Dependence	Overall Exposure
IGAD (East Africa)	High	Severely Limited	Very High (drought-prone)	Ongoing	High	Extremely High
ECOWAS (West Africa)	Mixed	Limited to Moderate	High	Fragile in Sahel Belt	High	High
SADC (Southern Africa)	Mixed	Moderate	High (Drought, floods)	Relatively Stable	Moderate	Moderate to High
AMU (North Africa)	Moderate to Strong	Better (Oil-driven)	Moderate to High	Transitioning regimes	Very high (Especially Egypt)	Moderate to High
SAARC (South Asia)	Moderate	Moderate	High (Floods, drought)	Nuclear Standoff Zone	Mixed (Net Importer overall)	Moderate
CARICOM (Caribbean)	High	Limited	High (Hurricane prone)	Generally Stable	Very High (Small Markets)	High

Note: Source: Author Compilation (Using information from World Bank, IMF, UNCTAD, FAO, EM-DAT, Fragile State Index, Uppsala Conflict Data Program).

Table 2. Comparative fragility matrix – IGAD member countries

Country	Currency Fragility	Limited Fiscal Space	Import Dependency With Little Substitution	Exposure To Climate Shocks	Instability	Overall Exposure
South Sudan	High	High	High	High	High	Extremely High
Somalia	High	High	High	High	High	Extremely High
Eritrea	High	High	Moderate	Moderate	Low	Very High
Sudan	High	High	High	Moderate	High	Very High
Ethiopia	High	Moderate	High	High	High	High
Djibouti	Low	Moderate	Moderate	High	Low	Moderate to High
Kenya	Moderate	Moderate	High	Moderate	Low	Moderate to High
Uganda	Moderate	Moderate	Moderate	High	Low	Moderate to High

Note: Source: Author Compilation (Using information from World Bank, IMF, UNCTAD, FAO, EM-DAT, Fragile State Index, Uppsala Conflict Data Program).

Wheat import in the IGAD bloc is handled entirely at the individual country level, depending on the national needs and severity of domestic shocks such as drought and conflict as seen in Figure 3. Country with a combination of high exposure to climate shocks and high instability tend to import more than those with relatively stable conditions, as domestic production is frequently disrupted and emergency procurement becomes the norm. This is case for Ethiopia, which recently embarked on an effort to reach national self-sufficiency in wheat production but recurring droughts, conflict-related displacement, and input shortages have continued to undermine domestic yields.

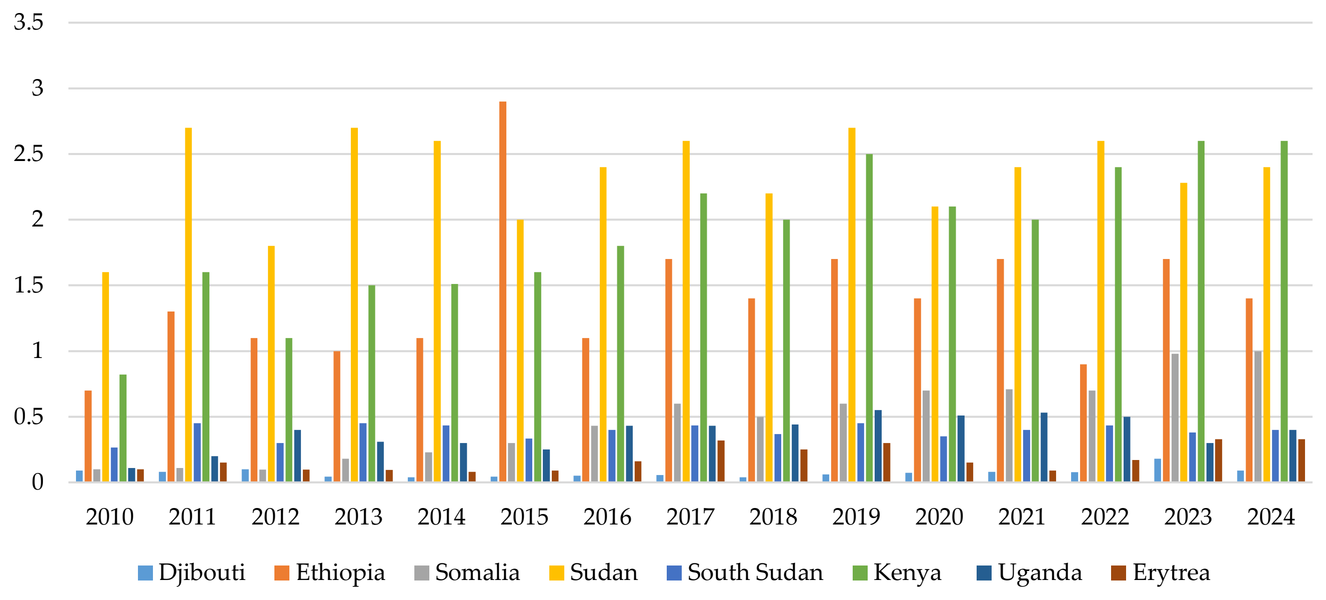

Figure 3. IGAD member countries wheat import per year (Source: Author Compilation (Using Indexmundi.com, Djibouti and South Sudan are estimated using respectively Ethiopia and Uganda Volume. Wheat import through Djibouti is mainly destined to Ethiopia while South Sudan procures wheat from Uganda)

As there is no regional purchasing strategy, no collective storage system, and no joint emergency response mechanism, each country acts on its own. This fragmented approach leads to reactive mechanism triggered by shortages or humanitarian emergencies—rather than based on pre-planned strategic reserve systems. In some cases, imports happen in a hurry after local crops fail or global prices surge, rather than in anticipation of such events. Even countries with some procurement capacity lack pro-activeness in the planning process (FAO, 2021; USAID, 2022).

The member countries import also exhibit a seasonal pattern, with volumes typically rising ahead of lean seasons or in anticipation of domestic shortfalls. For example, Ethiopia tends to ramp up wheat imports before the Meher harvest gap, while Sudan and Somalia adjust procurement based on rainfall forecasts and humanitarian needs. These seasonal surges, however, are not always well-coordinated or strategically planned, making countries more vulnerable when supply shocks occur unexpectedly.

Despite this lack of coordination, IGAD as a whole is a major wheat importer. The imports were on an upward trend as seen in Figure 4. The bloc imported over 8 million metric tons of wheat in 2024 campaign. This amount would place it among the top 5 wheat importers globally—alongside countries like Egypt, Indonesia, and China (USDA, 2023). But the lack of a joint procurement platform means IGAD countries miss out on potential advantages such as stronger bargaining power, shared transport logistics, and unified emergency reserves. individually, country pays individually—often under pressure—making the region more exposed and less competitive in the global market.

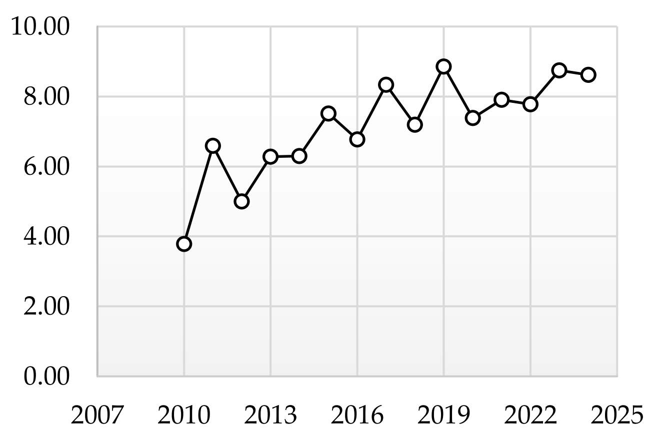

Figure 4. IGAD member countries combined wheat import per year (Source: Author Compilation (Using Indexmundi.com, Sum of individual countries imports)

Literature Review

As discussed in the theoretical background, there is an abundance of research exploring the price mechanics of wheat at the global level, especially how market shocks translate into volatility. Wheat prices are shaped by a combination of factors on both the supply and demand sides. On the supply end, studies have long established the role of climate variability, with droughts, floods, and extreme heat now becoming more frequent due to climate change (Wheeler & von Braun, 2013; Porter et al., 2014). At the same time, spikes in oil prices raise the cost of production and transportation, increasing the final price of wheat (Headey & Fan, 2010). Geopolitical disruptions—such as wars or trade bans—can further distort trade flows. The 2022 Russia-Ukraine war, for instance, disrupted one of the world's major grain corridors, causing a steep price surge (FAO, 2022c; World Bank, 2022). Another factor that adds fragility is the concentration of exports in a few countries—Russia, the EU, the US, Canada, and Australia. When any of these faces' disruptions, the ripple effects are global. Finally, chokepoints like the Black Sea corridor or the Suez Canal play a disproportionate role in maintaining trade flows, making the system highly sensitive to localized disruptions.

On the demand side, wheat is inelastic in the short term—people cannot easily replace it with alternatives—which means even small supply shocks can lead to big price jumps (Bobenrieth et al., 2013). Moreover, wheat trade in many countries is not consumer-driven but managed by governments and large millers, often with strategic stockpiling goals. During crises, states may even import more at high prices to avoid unrest. This behavior often contradicts standard economic models that expect demand to fall as prices rise. As Wright (2011) and Wright & Williams (1982) explain, this mismatch—rigid demand meeting unstable supply—makes the wheat market particularly vulnerable to cycles of spikes and shortages. When stocks are low, these effects are magnified, as seen during the 2007–2008 crisis. Lastly, policy responses like export bans, often meant to secure domestic markets, can actually make the global situation worse (Martin & Anderson, 2012).

On a parallel track, multilateral organizations have published policy papers addressing the challenges faced by low-income and fragile states in dealing with wheat supply shocks and price volatility. These contributions often approach the problem from a resilience-building perspective. FAO et al. (2024) has highlighted the importance of strengthening national grain reserves and regional early warning systems. USAID (2022) emphasizes the need to improve procurement strategies and storage capacity. The World Bank (2023) recommends integrated food security frameworks that include fiscal policy instruments, trade policy reforms, and targeted safety nets. However, these reports often remain broad in scope, and while they highlight the weaknesses, they do not always provide data-driven insights into the effectiveness of national or regional responses.

Post-2020 syntheses call for strengthening national reserves, targeted social protection, and macro-fiscal buffers alongside diversified sourcing to bolster resilience (FAO et al., 2024). Global reviews emphasize that elevated food and fertilizer costs, currency depreciation, and climate shocks continue to constrain access in lower-income regions, recommending risk-management tools and more predictable financing windows for crises (IFPRI, 2024). Complementary analyses document how conflict-related shocks and sanctions have tightened cereals markets and logistics, reinforcing the need for anticipatory procurement and regional coordination—issues central to our IGAD focus (OECD/FAO, 2022).

However, literature gets scarcer when it comes to the IGAD region. A handful of academic and institutional studies have touched on issues such as procurement delays, poor inter-agency coordination, and limited reserve capacity. FAO (2021) notes the lack of shared grain storage or joint procurement mechanisms across IGAD member states. Similarly, USAID (2022) points to a recurring pattern of reactive imports, often triggered by humanitarian emergencies or climatic shocks, rather than proactive strategies. Yet, most of these works are descriptive.

Going one step further, there is, to our knowledge, no empirical study that models how IGAD countries respond to global wheat price changes in a panel setting. There's also nothing that looks into the potential benefit of collective procurement or joint reserve systems from a data-driven angle. This paper tries to fill that gap by testing whether a shared response could make sense based on how countries react individually. In that sense, it hopes to bring something new—both as an analytical tool and as a policy input for future decision-making.

MATERIAL AND METHODS

Data Description

The dataset spans the first half of 2010 to the second half of 2022, comprising biannual observations across 26 time points. It covers the eight IGAD member states—Djibouti, Eritrea, Ethiopia, Kenya, Somalia, South Sudan, Sudan, and Uganda—and includes a global wheat price indicator. The price series is derived from the Chicago Red Wheat Commodity Index, sourced from Index Mundi, a trusted platform for consolidated commodity data, valued for its consistency and precision in capturing price fluctuations. Similarly, country-level wheat import volumes are obtained from Index Mundi, which aggregates trade data from governmental and international sources, ensuring cross-country comparability and data reliability. Using a single source for both price and import data enhances methodological consistency throughout the analysis.

For the panel analysis, the Chicago Red Wheat Index serves as the unified global wheat price series across all IGAD countries. Although country-specific price variations may arise from transport costs, exchange rates, or policy interventions, employing a single price index is justified for several reasons. First, IGAD nations are primarily price takers in global wheat markets, relying on similar suppliers or international aid programs. Second, local price formation in many of these countries is heavily regulated or shaped by external procurement, especially in fragile states. Third, a common benchmark facilitates consistent cross-country comparisons and aligns with standard practices in panel studies of global commodities. Thus, the Chicago Red Wheat Index provides a reliable and policy-relevant proxy for wheat price exposure across the region.

Descriptive statistics for all variables are presented in Table 3. Wheat import volumes differ significantly across countries, reflecting variations in population, dietary reliance, domestic production, and trade infrastructure. Sudan exhibits the highest average import volume, followed by Kenya and Ethiopia, while Djibouti and South Sudan have the lowest averages. High standard deviations in Ethiopia and Kenya indicate substantial temporal variability. The global wheat price has a mean of 260.30 USD, ranging from 149.3 to 454.7, underscoring significant volatility over the study period. Skewness and kurtosis values reveal non-normal distributions in several country series, particularly Ethiopia, with high skewness (2.34) and kurtosis (10.05), as confirmed by the Jarque-Bera test ($p < 0.001$). These properties emphasize the need for econometric methods robust to non-normality and heteroskedasticity in subsequent analyses.

Table 3. Descriptive statistics

Statistics	Djibouti	Eritrea	Ethiopia	Kenya	Somalia	South Sudan	Sudan	Uganda	Wheat
Mean	32038.46	79230.77	692307.7	889615.4	202115.4	194769.2	1169231.	194588.5	260.2996
Median	30125.00	65550.00	625500.0	914000.0	203000.0	192000.0	1152000.	183100.0	255.6650
Max.	70000.00	186000.0	2088000.	1550000.	468600.0	279000.0	1674000.	380000.0	454.7000
Min.	12040.00	25200.00	266000.0	312000.0	38000.00	90000.00	540000.0	42000.00	149.3000
Std. D.	14777.72	44594.31	357314.6	327814.5	131962.4	56584.31	339375.5	90595.35	77.56995
Skew.	1.160389	1.019180	2.337400	0.115371	0.339769	-0.251989	-0.250459	0.312959	0.684332
Kurt.	3.873152	3.170475	10.04770	2.363574	1.896809	2.066960	2.063653	2.336813	2.828654
J-B.	6.660768	4.532638	77.48421	0.496470	1.818700	1.218270	1.221638	0.900889	2.061148
Prob.	0.035779	0.103693	0.000000	0.780177	0.402786	0.543821	0.542906	0.637345	0.356802
Obs.	26	26	26	26	26	26	26	26	26

Note: Source: Index Mundi (2025)

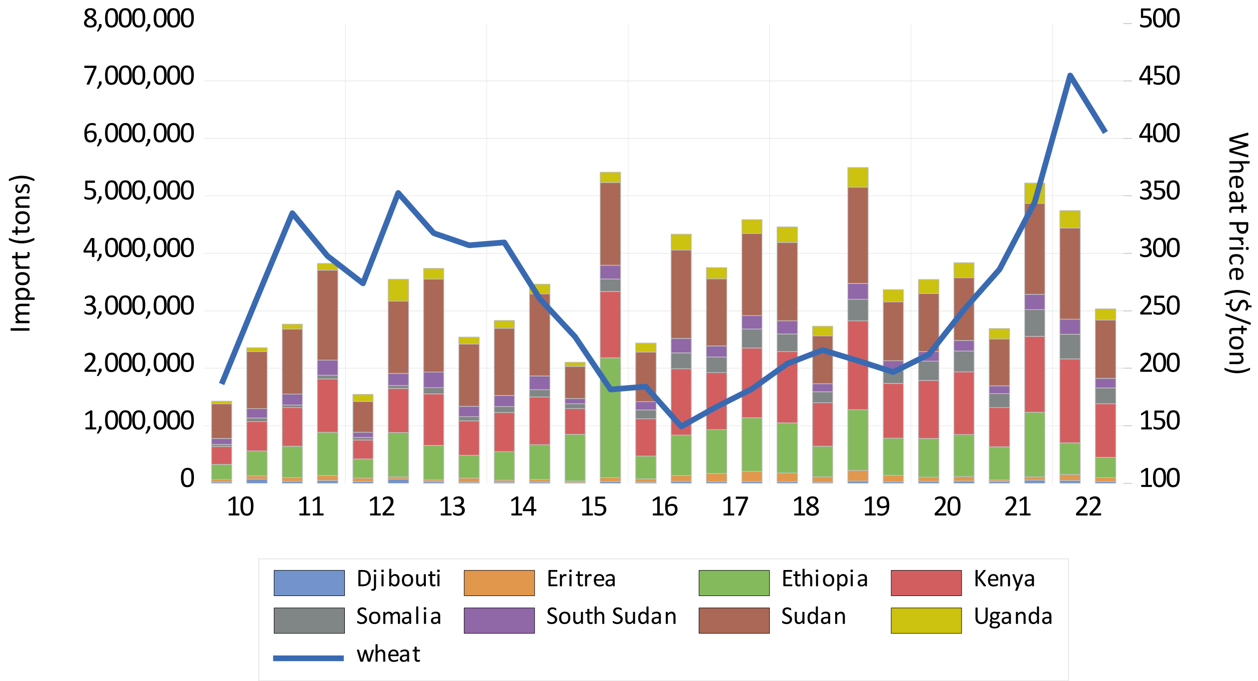

Figure 5. IGAD members' wheat imports and global wheat price (Source: Index Mundi, 2025)

Figure 5 depicts the interplay between total wheat import volumes in IGAD countries and global wheat prices from 2010 to 2022. Both series display significant variability, revealing a nuanced dynamic. During price surges in 2011, 2013, and notably 2022, import volumes do not consistently decrease, indicating relatively inelastic short-term demand for wheat in the region. In contrast, the mid-2010s show a concurrent decline in both prices and imports, suggesting potential demand-side limitations. Overall, the figure underscores a complex, potentially bidirectional relationship between prices and imports, which is subsequently validated by the Granger causality findings.

Country-Level Analysis: ARDL Approach

To examine the dynamic relationship between global wheat prices and wheat import volumes at the country level, we employ the Autoregressive Distributed Lag (ARDL) modeling framework, initially developed by Pesaran & Shin (1995) and further refined by Pesaran et al. (2001). The ARDL model is well-suited for small-sample time series data, enabling the estimation of both short-run and long-run relationships within a unified framework.

The ARDL approach is particularly effective when variables are a mix of I(0) (stationary) and I(1) (non-stationary) but not I(2) or higher, making it ideal for macroeconomic studies in developing and fragile contexts where data constraints are prevalent (Bölük & Mert, 2015). Unlike traditional cointegration methods that demand large sample sizes, the ARDL bounds testing approach performs reliably with smaller samples (N < 50) and is robust to issues like serial correlation, omitted variable bias, and potential endogeneity in regressors (Ozturk & Karagoz, 2012).

Prior to ARDL estimation, we conduct unit root tests, such as the Phillips & Perron (1988) (PP) test, to ensure no variables are integrated of order two, as I(2) variables would undermine the bounds testing procedure for cointegration by risking spurious regression results (Qamruzzaman & Jianguo, 2018).

For a dependent variable y_t (e.g., wheat imports) and an independent variable x_t (e.g., wheat price), the ARDL (p, q) model can be written as in Equation 1:

$$y_t = \alpha_0 + \sum_{i=1}^{p} \alpha_i \, y_{t-i} + \sum_{i=0}^{q} \beta_j \, x_{t-j} + \varepsilon_t \qquad (1)$$

where:

- y_t: dependent variable (e.g., wheat imports)
- x_t: independent variable (e.g., wheat price)
- p, q: lag of orders for dependent and independent variables, respectively

- ε_t: white noise error term
- α_0: constant term

To examine cointegration (i.e., long-run relationships), the ARDL model is often reparameterized into an Error Correction Model (ECM) form as in Equation 2:

$$\Delta y_t = \alpha_0 + \sum_{i=1}^{p-1} \delta_i \, \Delta y_{t-i} + \sum_{i=0}^{q-1} \theta_j \, x_{t-j} + \emptyset_1 y_{t-1} + \emptyset_2 x_{t-1} + \varepsilon_t \quad (2)$$

where:

- Δ : denotes the first difference
- $\emptyset_1$ and $\emptyset_2$: capture long-run relationship
- $The\ term\ \emptyset_1 y_{t-1} + \emptyset_2 x_{t-1}$ forms the error correction term, and significant negative coefficient on this term indicates adjustment toward long-run equilibrium.

ARDL models are estimated separately for each IGAD country in this study to capture their unique import sensitivities and price adjustment mechanisms. All variables are used in their natural logarithmic form, allowing the estimated coefficients to be interpreted as elasticities. The estimation and diagnostic procedures were carried out using EViews software, which supports flexible ARDL modeling, lag length selection, and bounds testing for cointegration.

Bloc-Level Analysis: Panel Granger Causality Approach

The panel Granger causality test in this study adopts the methodology of Juodis et al. (2021), an improvement over traditional fixed-effects panel model. This approach addresses common issues in macroeconomic panel data, such as cross-sectional dependence and individual-specific heterogeneity (Raifu et al., 2025). It accommodates country-specific dynamics and employs bootstrap-based inference, ensuring robustness in panels with moderate time dimensions and interdependent units (Simionescu & Schneider, 2022). As the method requires stationary variables, we first-difference the global wheat price and import volume series to achieve I(0) status, confirmed by second-generation panel unit root tests.

The strength of the Juodis et al. (2021) approach lies in its adaptability and reliability in complex empirical settings. Unlike conventional Granger causality tests, which often assume slope homogeneity and cross-sectional independence, this method accounts for the diverse structural characteristics and external vulnerabilities across IGAD countries. By permitting heterogeneous slope coefficients, it captures varied responses of import volumes to global wheat price changes. Additionally, bootstrap techniques improve the accuracy of statistical inference in small samples by correcting for potential biases in standard error estimation. This methodology is thus well-suited for analyzing causal dynamics in interconnected developing economies with diverse policy contexts.

The method is implemented using the xtgrangert command in Stata with the following specification:

xtgrangert depvar indepvar, maxlags(#) het bootstrap(#, seed(#))

This command estimates panel Granger causality where:

- depvar and indepvar are the first-differenced, stationary variables,
- maxlags(#) specifies the number of lags,
- het allows for heterogeneous panel structure, and
- bootstrap(#, seed(#)) ensures robust inference via bootstrap replication.

The test provides both individual coefficient estimates and a joint Wald statistic (HPJ test) to evaluate the null hypothesis of no Granger causality across the panel. This method is particularly well-suited for panels with a moderate time dimension (T) and cross-sectional units (N), as is the case with this study's dataset (Xiao et al., 2023). The method can be expressed as follows:

$$y_{i,t} = \alpha_i + \sum_{p=1}^{p} \beta_{i,p} \, y_{i,t-p} + \sum_{i=0}^{q} \gamma_{i,p} \, x_{i,t-p} + \varepsilon_{i,t} \quad (3)$$

where:

- $y_{i,t}$: dependent variable (e.g., wheat imports) for unit i at time t

- $x_{i,t}$: independent variable (e.g., wheat price)
- α_i : unit-specific intercept
- $\beta_{i,p}$: autoregressive coefficients (lags of y)
- $\gamma_{i,p}$: coefficients on lagged values of x
- p : maximum lag order
- $\varepsilon_{i,t}$: error term

In the context of the Juodis et al. (2021) panel Granger causality test, the null hypothesis states that the lagged values of the independent variable do not Granger-cause the dependent variable in any of the cross-sectional units. In other words, the past values of one variable (e.g., wheat prices) do not contain predictive information about the current values of another variable (e.g., wheat import volumes). Rejecting the null hypothesis implies the presence of Granger causality in at least some of the units in the panel, indicating a dynamic interdependence.

Before performing the panel Granger causality test, it is crucial to verify the stationarity of the variables involved, as the methodology assumes that the series are integrated of order zero I(0). Given the economic and structural linkages among IGAD countries, we first tested for cross-sectional dependence using Breusch-Pagan LM (Breusch & Pagan, 1980), Pesaran CD LM test (Pesaran, 2004), and LM adjusted Pesaran test (Pesaran et al., 2008). Detecting significant dependence among countries justifies the use of a second-generation panel stationarity test. Accordingly, we employed the Hadri test with bootstrap critical values, which is robust to cross-sectional dependence and suitable for moderate time dimensions. This two-step approach ensures that the stationarity diagnosis is both methodologically sound and tailored to the characteristics of our data.

RESULTS AND DISCUSSION

This study examined country-level dynamics using ARDL models to identify both short- and long-run relationships between wheat import volumes and global wheat prices across IGAD countries. It also complements these findings with bloc-level panel analyses to explore broader causal patterns and interdependencies. The results provide insight into how individual countries and the region as a whole respond to price shocks, offering a nuanced basis for policy interpretation.

Country-Level ARDL Results

The first stage of the empirical analysis focuses on country-specific dynamics using the Autoregressive Distributed Lag (ARDL) modeling framework. This method is well-suited for small samples and allows for mixed integration orders among variables, making it ideal for the diverse economic conditions found within the IGAD region. Prior to model estimation, we test for the order of integration of each variable to ensure the validity of the ARDL bounds testing procedure.

Unit Root Test Results

Before estimating the ARDL models, we conducted stationarity tests to ensure that the time series variables meet the integration conditions required for the ARDL bounds testing approach. Specifically, we employed the Phillips & Perron (1988) (PP) unit root test, which is well-suited for small sample sizes and allows for heteroskedasticity and autocorrelation in the error terms—a common feature in macroeconomic time series, especially in fragile or conflict-affected countries like those in the IGAD region.

The ARDL model, as developed by Pesaran et al. (2001), permits the inclusion of regressors that are integrated of order zero I(0) or order one I(1), but not of order two I(2). Thus, it is critical to verify that none of the variables in the model are I(2), which would invalidate the use of the ARDL approach.

Table 4 presents the PP test statistics for the wheat import series of each IGAD country and the global wheat price series. The results show a mix of integration orders across the countries. The import series for Djibouti, Ethiopia, Kenya, South Sudan, Sudan, and Uganda are stationary at level I(0), as their test statistics exceed the critical values for rejecting the null hypothesis of a unit root. On the other hand, the series for Eritrea and Somalia are found to be stationary only after first differencing I(1). This variation is acceptable within the ARDL framework, which allows a combination of I(0) and I(1) regressors. Notably, the global wheat price series is integrated of order one I(1), as expected for international commodity price data.

Table 4. Unit root test results

Country	Level		First Difference		Conclusion (95%)
	Intercept	Intercept & Trend	Intercept	Intercept & Trend	
Djibouti	-4.383	-4.300	-12.336	-21.998	I(0)
Eritrea	-2.736	-2.757	-6.915	-6.761	I(1)
Ethiopia	-5.151	-5.034	-12.704	-25.257	I(0)
Kenya	-4.615	-7.244	-21.327	-27.984	I(0)
Somalia	-1.842	-4.283	-12.120	-13.517	I(1)
South Sudan	-9.562	-13.170	-27.721	-22.554	I(0)
Sudan	-9.552	-11.716	-21.763	-22.595	I(0)
Uganda	-3.682	-4.482	-8.558	-9.782	I(0)
Wheat Price	-1.405	-1.339	-4.031	-4.171	I(1)

Note: Critical values for the PP unit root test are -3.724 (1%), -2.986 (5%), and -2.633 (10%) under the intercept specification, and -4.374 (1%), -3.603 (5%), and -3.238 (10%) under the intercept and trend specification.

Table 5. ARDL long run estimates

Variables	Djibouti	Eritrea	Ethiopia	Kenya	Somalia	South Sudan	Sudan	Uganda
Wheat	0.344	-1.899	-0.506	-0.614	4.775	-0.129	-0.130	-0.466
	(0.200)	(0.001)	(0.055)	(0.048)	(0.764)	(0.47)	(0.468)	(0.375)
Constant	8.353	21.55	16.186	17.022	-10.020	12.855	14.650	14.706
	(0.000)	(0.000)	(0.000)	(0.000)	(0.879)	(0.000)	(0.000)	(0.000)
ARDL Bound Test								
F-Statistics	10.606***	5.584**	11.079***	10.360***	5.231**	19.642***	19.645***	5.307**
Model Selection	(1, 1)	(1, 3)	(1, 0)	(1, 2)	(3, 4)	(1,2)	(1, 2)	(1, 2)
Model Statistics								
R-Square	0.308	0.561	0.151	0.288	0.902	0.344	0.345	0.250
Adj. R-Square	0.209	0.431	0.739	0.138	0.841	0.206	0.207	0.092
F-Statistics	3.118**	4.339***	1.958	1.924	14.964***	2.499*	2.502*	1.582
Diagnostics								
Normality	1.144	3.072	2.329	0.794	0.913	1.753	1.732	0.067
Serial Correlation	1.535	0.675	2.136	1.000	2.812	0.265	0.262	4.427**
Heteroscedasticity	2.280	0.353	0.269	0.521	0.767	1.355	1.365	1.546
CUSUM Stability	Stable	Stable	Stable	Instable	Stable	Stable	Stable	Stable
CUSUM Sq. Stability	Stable	Stable	Stable	Stable	Stable	Stable	Stable	Stable

Note: Critical values for the ARDL F-bounds test (finite sample, n=30) are 3.797 (10%), 4.663 (5%), and 6.760 (1%). Heteroskedasticity Test: Breusch-Pagan-Godfrey

Table 6. ARDL short run estimates

Variables	Djibouti	Eritrea	Ethiopia	Kenya	Somalia	South Sudan	Sudan	Uganda
D(Wheat)	1.715 (0.007)	-0.335 (0.626)	-0.559 (0.061)	-0.036 (0.945)	0.051 (0.920)	-0.209 (0.626)	-0.209 (0.623)	0.672 (0.302)
D(Wheat (-1))		1.230 (0.138)		1.266 (0.028)	-0.008 (0.992)	0.957 (0.039)	0.957 (0.039)	0.234 (0.724)
D(Wheat (-2))		1.425 (0.067)			-1.080 (0.087)			
D(Wheat (-3))					-1.047 (0.073)			
Cointegration (ECM)	-1.173 (0.000)	-0.852 (0.001)	-1.130 (0.000)	-1.037 (0.000)	-0.064 (0.662)	-1.405 (0.000)	-1.405 (0.000)	-0.720 (0.000)

Long-Run Relationships

The results of the ARDL long-run estimations are presented in Table 5. All eight IGAD countries demonstrate the existence of a long-run relationship between wheat import volumes and global wheat prices, as confirmed by the ARDL bounds testing procedure. The F-statistics for each model exceed the critical threshold values at conventional significance levels (1%, 5%, or 10%), indicating the presence of cointegration between the dependent and independent variables.

The long-run coefficients associated with the wheat price variable vary in both magnitude and sign across countries, reflecting the heterogeneous structural and economic characteristics of IGAD member states. Some countries exhibit negative long-run elasticities, suggesting that rising wheat prices are associated with lower import volumes in the long term, while others show either positive or statistically insignificant relationships. This variation aligns with differences in procurement strategies, aid dependency, foreign exchange constraints, and domestic policy responses.

It is important to note that the presence of cointegration in all cases provides a robust foundation for interpreting both short- and long-run dynamics. The model diagnostics further support the reliability of the ARDL specifications, with most models passing tests for normality, heteroscedasticity, and structural stability. The relatively high R-squared values in several cases also suggest that a meaningful proportion of the variation in import volumes is explained by the global wheat price over the long term.

Short-Run Dynamics

The short-run dynamics estimated through the ARDL error correction models are reported in Table 6. These results capture the immediate or lagged responses of wheat import volumes to changes in global wheat prices across IGAD countries. While the short-run coefficients vary in sign and statistical significance, several countries exhibit meaningful short-run sensitivity, indicating that import decisions in the region can be influenced by short-term price fluctuations, though not uniformly.

More importantly, the error correction terms (ECM) across most models are negative and statistically significant at the 1% level, confirming the existence of a stable long-run relationship and validating the error correction framework. The magnitude of the ECM coefficients indicates the speed at which deviations from long-run equilibrium are corrected following a short-term shock. In most cases, these coefficients suggest a relatively fast adjustment process, with a substantial portion of disequilibrium corrected within a single period. Somalia is the only exception, showing a statistically insignificant ECM term, likely reflecting weak or delayed adjustment mechanisms in that context.

The short-run coefficients for differenced wheat prices and their lags further highlight the heterogeneity across IGAD member states. Some countries respond immediately, while others exhibit delayed responses over one or more lags.

Country-Specific Interpretations

The ARDL results have been presented for each IGAD member country individually, highlighting both long-run and short-run relationships between global wheat prices and national import volumes. While all countries exhibit cointegration, the direction, magnitude, and statistical significance of their responses vary considerably, reflecting differences in economic structure, import dependency, aid reliance, and policy frameworks. These interpretations draw from the earlier empirical outputs but place them in the context of each country's unique circumstances.

Djibouti

The ARDL bounds test for Djibouti yields an F-statistic of 10.606 (significant at 1%), confirming cointegration between wheat prices and imports. The long-run elasticity is 0.344 (p=0.200, not significant), indicating that a 1% increase in wheat prices would increase imports by 0.34%, reflecting a positive but statistically insignificant relationship. In the short run, the elasticity is 1.715 (p=0.007), significant at 1%, showing that imports increase by 1.72% in response to a 1% price increase, suggesting high price elasticity in the short term likely due to Djibouti's reliance on imported wheat and limited substitution. The ECM coefficient is -1.173 (p=0.000), indicating rapid adjustment (117% correction per period) toward the long-run equilibrium. However, these results need to be read with caution. Djibouti is mainly a re-export hub, serving Ethiopia's wheat demand rather than its own consumption. The pattern is therefore more a reflection of Ethiopian procurement routed through Djibouti port than of Djibouti itself.

Eritrea

The ARDL bounds test yields F = 5.584 (significant at 5%), confirming cointegration. The long-run elasticity is -1.899 (p=0.001, significant at 1%), indicating a 1% increase in wheat prices reduces imports by 1.9%, showing strong price sensitivity likely due to foreign exchange constraints. Short-run elasticities are not significant except for a marginally significant D(Wheat(-2)) at 1.425 (p=0.067), indicating a delayed positive response, potentially due to procurement processes or policy adjustments. The ECM is -0.852 (p=0.001), confirming stable and relatively fast adjustment toward equilibrium (85% per period). Eritrea's price responsiveness in the long run may reflect import rationing, foreign exchange scarcity, and prioritization of essential imports, resulting in import reductions during price surges.

Ethiopia

Ethiopia's ARDL bounds test yields F = 11.079 (significant at 1%), indicating cointegration. The long-run elasticity is -0.506 (p=0.055, marginally significant), indicating that a 1% increase in wheat prices leads to a 0.51% reduction in imports, consistent with Ethiopia's efforts to substitute imports with domestic production. The short-run elasticity is -0.559 (p=0.061), marginally significant, reinforcing the price-sensitive nature of Ethiopia's import behavior. The ECM coefficient is -1.130 (p=0.000), indicating rapid correction (113% per period) toward long-run equilibrium. This reflects Ethiopia's import substitution policies and possible fiscal discipline on imports in the face of rising prices.

Kenya

Kenya's ARDL bounds test shows F = 10.360 (significant at 1%), confirming cointegration. The long-run elasticity is -0.614 (p=0.048, significant), implying that a 1% increase in wheat prices reduces imports by 0.61% in the long run. Short-run elasticity is insignificant contemporaneously (-0.036, p=0.945) but becomes significantly positive at lag one (1.266, p=0.028), indicating a 1% price increase increases imports by 1.27% after one period, suggesting a delayed response to price increases, possibly due to procurement contract structures. The ECM coefficient is -1.037 (p=0.000), indicating rapid correction (104% per period) to the equilibrium path. Kenya's pattern may reflect partial local production, policy buffers, and structured import scheduling that causes a lagged but strong import reaction to price changes.

Somalia

Somalia's ARDL bounds test result is F = 5.231 (significant at 5%), confirming cointegration. The long-run elasticity is 4.775 (p=0.764, not significant), suggesting wheat prices do not meaningfully impact import volumes in the long run. Short-run elasticities are mostly insignificant except for D(Wheat(-2)) = -1.080 (p=0.087) and D(Wheat(-3)) = -1.047 (p=0.073), marginally significant, indicating a 1% increase in wheat prices reduces imports by ~1% after 2–3 periods. The ECM coefficient is -0.064 (p=0.662, insignificant), reflecting weak evidence of adjustment toward equilibrium. These results align with Somalia's aid-dependent wheat supply and informal trade, which decouples import behavior from market price signals.

South Sudan

South Sudan's ARDL bounds test yields F = 19.642 (significant at 1%), confirming strong cointegration. The long-run elasticity is -0.129 (p=0.470, insignificant), indicating a weak long-run price-import relationship. In the short run, the immediate effect is insignificant, but D(Wheat(-1)) = 0.957 (p=0.040, significant), showing that a 1% price increase in the previous period increases imports by 0.96% currently, suggesting delayed import responses due to administrative lags or aid delivery timing. The ECM coefficient is -1.405 (p=0.000), indicating very rapid adjustment (140% per period) to long-run equilibrium. This pattern may reflect reliance on external food aid and volatile import timing in a conflict-affected environment.

Sudan

Sudan's ARDL bounds test shows F = 19.645 (significant at 1%), indicating cointegration. The long-run elasticity is -0.130 (p=0.468, insignificant), indicating weak responsiveness of imports to price changes. Short-run effects are not significant, while the ECM is -1.405 (p=0.000), showing rapid adjustment (140% per period) toward the long-run equilibrium. This pattern may result from Sudan's economic volatility, inflation, currency depreciation, and import subsidy or aid programs that buffer wheat imports from direct price responsiveness.

Uganda

Uganda's ARDL bounds test yields F = 5.307 (significant at 5%), confirming cointegration. The long-run elasticity is -0.466 (p=0.375, insignificant), indicating limited long-run price elasticity of imports. Short-run elasticity is 0.672 (p=0.302, insignificant), and the ECM is -0.720 (p=0.000), showing stable adjustment (72% per period) toward equilibrium. Uganda's low wheat consumption, the availability of local substitutes, and stable domestic demand likely explain the limited responsiveness of imports to price changes.

General Evaluation

The ARDL bounds testing confirms that all countries in the analysis exhibit cointegration between wheat prices and import volumes, indicating the existence of stable long-run relationships despite short-term fluctuations. In terms of long-run elasticities, Eritrea (-1.90), Kenya (-0.61), and marginally Ethiopia (-0.51) demonstrate significant negative responsiveness, suggesting that higher wheat prices lead to meaningful reductions in import volumes in these countries over time. This aligns with economic realities such as foreign exchange constraints and import substitution policies, leading to price-sensitive import demand.

In the short run, wheat price responsiveness varies across countries with biannual frequency, meaning each lag reflects a 6-month delay. Djibouti shows immediate, highly significant positive elasticity (+1.72, p=0.007), indicating that a 1% increase in wheat prices leads to a 1.72% rise in imports within the same 6-month period, reflecting inelastic, food security-driven import demand despite rising costs. Ethiopia exhibits a marginally significant immediate negative elasticity (-0.56, p=0.061), suggesting that price increases reduce imports by 0.56% within six months, consistent with substitution or import reduction behavior under foreign exchange or policy constraints. Kenya (+1.27, p=0.028), South Sudan (+0.96, p=0.039) and Sudan Sudan (+0.96, p=0.039) display significant positive elasticities at a one-period lag, indicating that wheat price increases lead to higher imports after six months, possibly reflecting procurement cycles, administrative processes, or aid delivery lags. Additionally, Eritrea (+1.43, p=0.067) and Somalia (-1.08, p=0.087; -1.05, p=0.073) demonstrate marginally significant effects at 12–18-month lags, indicating delayed import responsiveness where Eritrea increases imports after a year of price increases, while Somalia reduces imports with a longer delay, likely reflecting aid delivery dynamics or informal trade adjustments. These findings highlight the diversity in short-run price elasticity across countries, shaped by their specific institutional structures, aid dependencies, import reliance, and policy environments, despite all countries maintaining long-run equilibrium relationships.

The Error Correction Mechanism (ECM) coefficient captures the speed at which deviations from the long-run equilibrium adjust back following short-run shocks. Economically, a negative and significant ECM indicates that if wheat import volumes deviate from their long-run relationship with prices, a portion of this disequilibrium is corrected in each period (here, every 6 months), reflecting how quickly trade adjusts back toward equilibrium after shocks such as price spikes, policy changes, or supply disruptions. Countries with high ECM magnitudes adjust quickly to shocks, reflecting rapid and flexible trade system responses, while countries with lower ECM magnitudes exhibit slower, more gradual adjustments, indicating structural or policy-related frictions delaying convergence toward equilibrium. The Error Correction Mechanism (ECM) coefficients across the countries are negative and highly significant (except for Somalia), confirming rapid adjustment toward the long-run equilibrium after short-run deviations. Notably, South Sudan and Sudan exhibit the fastest adjustment speeds (~140% correction per period), followed by Djibouti (117%), Ethiopia (113%), and Kenya (104%), while Uganda (72%) and Eritrea (85%) also maintain stable long-run adjustment paths. Somalia, with an insignificant ECM, indicates weaker adjustment dynamics, consistent with its aid-dependent and informal trade environment. Comparative summary of elasticity significance is presented in Table 7.

Bloc-Level Panel Granger Causality Results

The second stage of the empirical analysis shifts from individual country behavior to regional dynamics, using a panel Granger causality framework to assess the direction and strength of the relationship between global wheat prices and import volumes across the IGAD bloc. Before estimating the panel model, it is important to test the underlying data structure for interdependencies and parameter consistency across countries to ensure the validity and robustness of the panel-based inference.

Cross-Sectional Dependence and Homogeneity Tests

Before proceeding with the panel Granger causality analysis, we tested the suitability of the panel data structure by examining cross-sectional dependence and slope homogeneity. These diagnostics are essential in panel settings where countries may be interlinked through shared external exposures or similar structural characteristic conditions likely present among IGAD member states.

Table 7. Comparative summary of elasticity significance

Country	Long-run Elasticity (Significance & Sign)	Short-run Elasticity (Significance & Timing)
Djibouti	Not significant (+)	Significant immediate (+)
Eritrea	Significant (-)	Marginal at lag 2 (+)
Ethiopia	Marginally significant (-)	Marginally immediate (-)
Kenya	Significant (-)	Significant at lag 1 (+)
Somalia	Not significant (+)	Marginal at lag 2-3 (-), ECM not Significant
South Sudan	Not significant (-)	Significant at lag 1 (+)
Sudan	Not significant (-)	Insignificant
Uganda	Not significant (-)	Insignificant

Table 8. Cross-section dependence and homogeneity tests

Test	Price		Export	
	Statistic	Prob.	Statistic	Prob.
Breusch-Pagan LM	728.00	0.000	241.25	0.000
Pesaran scaled LM	93.54	0.000	28.49	0.000
Bias-corrected scaled LM	93.38	0.000	28.33	0.000
Pesaran CD	26.98	0.000	14.42	0.000
Delta Tilde	-1.970	0.976	0.999	0.159
Delta Tilde Adjusted	-2.094	0.982	1.062	0.144

Table 9. Panel unit root test

	Test	Price		Import	
		Constant	Constant & Trend	Constant	Constant & Trend
Level	t-bar statistics	-0.398	5.525	4.538	3.526
	Bootstrap CV 10%	3.266	4.247	2.087	2.941
	Bootstrap CV 5%	4.405	5.147	2.712	3.462
	Bootstrap CV 1%	7.146	6.488	4.502	4.768
First Difference	t-bar statistics	-0.046	5.322	0.033	0.686
	Bootstrap CV 10%	3.569	4.477	2.387	3.491
	Bootstrap CV 5%	4.805	5.330	3.635	4.281
	Bootstrap CV 1%	7.039	6.609	5.341	5.680

Note: Long-run variance estimator: Bartlett; Number of Bootstrap replications: 1000.

As shown in Table 8, the Breusch-Pagan LM statistic (728.00, p = 0.000), the Pesaran scaled LM (93.54, p = 0.000), Bias-corrected scaled LM test (93.38, p=0.000), and the Pesaran CD test (26.98, p = 0.000) all strongly reject the null hypothesis of cross-sectional independence. Given our panel structure—large time dimension (T = 180) and relatively small cross-sectional dimension (N = 8)— the Pesaran CD test is especially appropriate and robust. These results confirm the presence of significant interdependence among IGAD countries, which is theoretically expected, particularly because the countries are all exposed to the same global wheat price series. Using a common exogenous variable introduces a natural linkage across panel units, reinforcing the economic interpretation of cross-sectional dependence in this context.

In contrast, the Delta Tilde test (-1.970, p = 0.976) and its adjusted version (-2.094, p = 0.982) fail to reject the null hypothesis of slope homogeneity, suggesting that countries may exhibit similar average responses to global wheat price shocks in the Granger causality framework. Given the structural similarities across IGAD member states—such as high import dependency, fiscal limitations, and exposure to global markets—this result is theoretically reasonable. However, to ensure robustness regardless of these findings, the panel Granger causality test employed in this study, developed by Juodis et al. (2021) and implemented using the xtgrangert command in Stata, explicitly allows for slope heterogeneity and adjusts for cross-sectional dependence through a bootstrap-based inference procedure. Therefore, the presence of either cross-sectional dependence or (non-)homogeneity does not compromise the validity of the results presented in the subsequent panel causality analysis.

Panel Unit Root Tests

To assess the stationarity properties of the panel data, we employed the second-generation Hadri (2000) panel stationarity test with bootstrap-based critical values, which is appropriate in the presence of cross-sectional dependence. Unlike traditional first-generation unit root tests, the Hadri test assumes stationarity under the null hypothesis and tests for the presence of unit roots in the panel. The use of bootstrap distributions further enhances robustness by correcting for potential cross-sectional correlation and small-sample bias, which are particularly relevant given the interconnected nature of IGAD economies and the shared global wheat price series.

The test was conducted under both constant and constant-plus-trend specifications. As shown in Table 9, the t-bar statistic for the wheat price series at level is -0.398, which falls well below the 10% bootstrap critical value of 3.266, leading to rejection of the null hypothesis of stationarity. Similarly, the import volume series at level yields a t-bar of 4.538, also below its critical threshold (2.087), again indicating non-stationarity at level. However, when both series are first-differenced, the test statistics rise significantly—5.322 for wheat price and 0.686 for imports—both exceeding their respective bootstrap critical values, meaning that we fail to reject the null of stationarity in first differences.

These findings confirm that both global wheat prices and import volumes are integrated of order one, I(1), and justify the use of Granger causality analysis in first differences. The stationarity of the differenced series ensures that the panel regression results are not spurious and that the assumptions underlying the heterogeneous panel Granger causality test are satisfied.

Granger Causality Findings

To examine the causal relationship between global wheat prices and wheat import volumes within the IGAD bloc, we applied the heterogeneous panel Granger non-causality test developed by Juodis et al. (2021), implemented in Stata using the xtgrangert command. The test was executed with the following options:

```
xtgrangert D.export D.wheatprice , maxlags(2) het bootstrap (100, seed(20171020))
```

This specification uses two lags of the differenced series (biannual frequency), allows for heterogeneous dynamics across countries (het option), and employs bootstrap-based inference with 100 replications to ensure robustness to cross-sectional dependence (bootstrap option with a fixed seed for reproducibility).

The results, presented in Table 10, show that the lagged value of global wheat price has a positive and statistically significant effect on wheat import volumes. Specifically, the coefficient on wheatprice(-1) is 0.491 with a z-statistic of 2.57 and a p-value of 0.010, indicating a significant predictive relationship. The HPJ Wald test statistic further supports this result, with a test value of 6.604 and a bootstrap-adjusted p-value of 0.010.

Taken together, these results lead us to reject the null hypothesis that wheat prices do not Granger-cause import volumes. This implies that, within the panel of IGAD countries, past movements in global wheat prices help predict changes in national import volumes, although the strength and timing of this relationship may differ across countries.

To test the reverse relationship—whether wheat import volumes Granger-cause global wheat prices—we employed the same heterogeneous panel Granger non-causality framework using the following Stata command:

```
xtgrangert D.wheatprice D.export, maxlags(2) het bootstrap(100, seed(20171020))
```

Table 10. Results for the panel causality test

	Coefficient	Std. Error	z	$P > \|z\|$
$wheatprice_{(-1)}$	***0.491***	0.191	**2.57**	0.010
JKS Non-Causality Result	**HPJ Walt Test**	6.604	**P-Value**	0.010

Table 11. Results for the panel causality test

	Coefficient	Std. Error	z	$P > \|z\|$
$export_{(-1)}$	***0.048***	0.009	5.04	0.000
JKS Non-Causality Result	**HPJ Walt Test**	25.362	**P-Value**	0.000

This test again uses two lags of the differenced variables, accommodates heterogeneous country-specific dynamics, and applies bootstrap-based inference to correct for cross-sectional dependence.

The results, reported in Table 11, show that the lagged value of import volumes has a positive and highly significant effect on wheat prices. The estimated coefficient for export(-1) is 0.048, with a z-statistic of 5.04 and a p-value of 0.000. The HPJ Wald test strongly confirms this causal relationship, with a test statistic of 25.362 and a bootstrap-adjusted p-value of 0.000.

These findings lead us to reject the null hypothesis that import volumes do not Granger-cause wheat prices. This result is noteworthy—and somewhat unexpected—given IGAD's relatively modest share in the global wheat market. The causal influence may reflect localized market volatility, timing shifts in bulk procurement, or aggregate demand pressure that feeds back into global price expectations. The fact that such a relationship appears in the absence of coordinated import strategies suggests that collective regional behavior, even if unintentional, may generate measurable signals in international markets. This insight holds meaningful implications for policy, particularly with respect to exploring regional procurement coordination and buffer stock strategies.

Impulse Response Functions

To complement the Granger causality results and explore the dynamic interactions over time, Impulse Response Functions (IRFs) were derived from a panel VAR model. The IRFs trace the response of each variable to a one-standard-deviation shock in the other, over a horizon of five periods (equivalent to 2.5 years, given the biannual frequency of the data).

As illustrated in Figure 6, the top-right panel (D_wheatprice → D_export) shows that a positive shock to global wheat prices leads to a temporary increase in wheat import volumes in the IGAD bloc, peaking in the second period before gradually declining. This pattern aligns with the earlier panel Granger causality findings, reinforcing the idea that price signals influence short-term procurement decisions or emergency import responses.

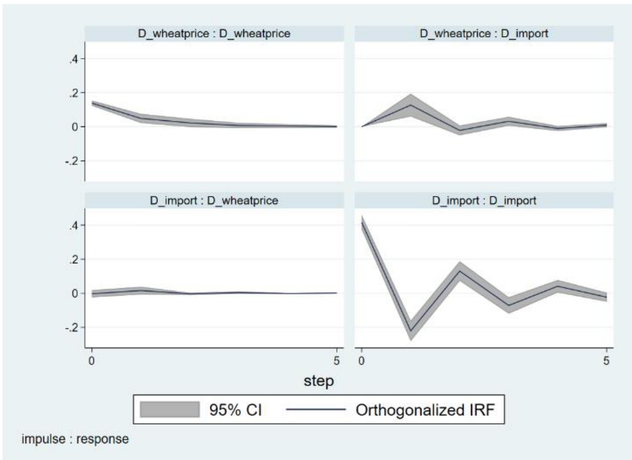

Figure 6. Impulse response functions (IRFS)

Conversely, the bottom-left panel (D_export → D_wheatprice) reveals that a shock to IGAD's aggregate import volumes also has a mild but persistent positive effect on global wheat prices. While this result may initially appear counterintuitive given the bloc's relatively small share in global wheat trade, it suggests that regional demand surges—particularly under stress conditions—can have ripple effects on international markets, possibly by affecting expectations or tightening localized supply channels.

Overall, the IRFs confirm a bidirectional relationship between wheat prices and import volumes, with feedback effects evolving over several periods. These dynamics underscore the importance of timing and coordination in wheat procurement across IGAD countries, particularly during episodes of global price volatility.

This study investigates the response of wheat import volumes in IGAD countries to global wheat price fluctuations, using a dual-method approach combining country-level ARDL models with bloc-level heterogeneous panel Granger causality analysis. The findings reveal both anticipated and unexpected dynamics, offering key policy implications for food security and trade coordination in the region.

At the country level, ARDL results confirm a long-run cointegrating relationship between wheat prices and import volumes across all IGAD member states. However, price elasticities vary significantly. Ethiopia, Kenya, and Eritrea exhibit strong negative long-run elasticities, indicating that higher prices reduce imports over time, likely due to domestic substitution, foreign exchange limitations, or policy constraints. Conversely, Djibouti and South Sudan show positive short-run elasticities, suggesting imports increase despite price rises, driven by urgent needs, limited local alternatives, or aid-driven procurement. These findings highlight the diverse wheat import behaviors across IGAD, influenced by factors such as import dependency, institutional capacity, and geopolitical fragility.

The bloc-level analysis reinforces these country-specific insights. Tests for cross-sectional dependence and homogeneity confirm interlinked wheat import behaviors across IGAD countries, supporting the use of second-generation panel methods. The panel Granger causality test, robust to cross-sectional dependence and heterogeneity, identifies significant bidirectional causality between wheat prices and import volumes. Global price changes predict IGAD's import patterns, but, surprisingly, the bloc's collective imports also influence global price movements, despite IGAD's modest role in global wheat trade. This feedback effect may stem from timing mismatches, demand surges, or market perceptions of regional instability.

Collectively, these results underscore the need for coordinated wheat procurement strategies across the IGAD bloc. The observed differences in short-run and long-run responsiveness highlight structural vulnerabilities that regional cooperation could address. Joint procurement mechanisms, regional grain reserves, or coordinated price-risk management tools, such as futures contracts or hedging instruments, could mitigate exposure to global price volatility and ensure stable access to this essential commodity.

This study enriches the sparse literature on commodity trade sensitivity in Eastern Africa by integrating macroeconomic time series methods with a regional development perspective. The dual-method approach captures both country-specific dynamics and systemic bloc-wide patterns, offering insights that single-method studies might overlook. As global food markets grow increasingly volatile, evidence-based strategies like those proposed here are critical for enhancing economic and food resilience in vulnerable regions like IGAD.

CONCLUSION

From a policy standpoint, the paper offers three key recommendations:

- Enhance regional coordination in wheat procurement to increase bargaining power and stabilize domestic markets.
- Invest in domestic production and substitution capacity where feasible, especially in countries showing strong negative long-run elasticities.
- Establish contingency frameworks, such as emergency reserves or import financing buffers, to address price-driven import surges in fragile states.

To make these recommendations more tangible, IGAD countries can draw useful lessons from other regions that have set up similar mechanisms. One example is the ECOWAS Regional Food Security Reserve, created in 2013 to complement national reserves and provide quick support during crises. It works through a structured governance framework, pooled country contributions, and a regional coordination unit. The reserve has been activated several times to help member states facing droughts and price spikes (ECOWAS, 2013; FAO, 2020). Another example is the ASEAN+3 Emergency Rice Reserve (APTERR), which is based on pre-agreed stockpiles and flexible release mechanisms; this arrangement has helped stabilize rice markets and deliver rapid emergency grain to member countries when shocks occur (APTERR Secretariat, 2022). At the national level, India's wheat buffer stock program provides a practical model of how strategic reserves can stabilize domestic markets. The Food Corporation of India maintains buffer norms that trigger procurement and release depending on market conditions, helping to smooth prices and maintain availability during shocks (Government of India, 2017).

For IGAD, a realistic path would be to start with national strategic stocks in key transit or gateway countries—such as Djibouti, Kenya, or Sudan—while gradually building a regional reserve framework coordinated by IGAD or a dedicated agency. This could be combined with joint procurement arrangements and, over time, the use of forward contracts or hedging instruments to manage price risks collectively. A governance charter could define participation rules, cost-sharing, and release criteria, and existing humanitarian corridors and logistics hubs (e.g., the Djibouti–Addis corridor) could serve as initial reserve sites. Over time, this could evolve into a more integrated regional reserve system, strengthening the bloc's bargaining power and resilience to external shocks.

However, the study has several limitations. First, the dataset, covering biannual observations from 2010 to 2022, includes only 26 time points, which may limit the detection of short-term shocks or policy interventions occurring at higher frequencies. While sufficient for ARDL and panel causality analyses, this restricts temporal granularity. Second, the focus on wheat price and import volume excludes other relevant factors such as exchange rates, domestic production, food aid, or broader macroeconomic indicators (e.g., inflation, conflict intensity). This narrow scope isolates the price-import relationship but may miss key contextual drivers. Third, while the panel Granger causality test is robust to cross-sectional dependence and heterogeneity, alternative methods like panel vector autoregression (PVAR), time-varying parameter models, or machine learning could provide additional insights.

Future research could address these limitations by extending the time horizon and using higher-frequency data (e.g., quarterly or monthly) to better capture short-term shocks and policy changes. Incorporating additional variables, such as transportation costs, domestic policy responses, or international aid flows, would offer a more comprehensive view of wheat import dynamics in fragile contexts. Additionally, exploring spillover effects across IGAD countries, given their interconnected trade routes and shared vulnerabilities, could be pursued using spatial econometric or network-based approaches.

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Compliance with Ethical Standards

Authors' Contributions

AMD: Conceptualization, Writing – original draft, Investigation.

AA: Supervision, Writing – review & editing, Methodology, Formal Analysis.

All authors read and approved the final manuscript.

Conflict of Interest

The authors declare that there is no conflict of interest.

Ethical Approval

For this type of study, formal consent is not required.

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Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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The authors used generative-AI tools (OpenAI ChatGPT) only to help with readability, phrasing, and some brainstorming for a few narrative sections. All the actual research work — including the data collection, econometric modeling and the analysis remain the sole responsibility of the authors and bear full responsibility for the content as submitted.

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Economic Assessment of Removal of Abandoned, Lost, or Otherwise Discarded Fishing Gear (ALDFG) From Northeastern Mediterranean Sea

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ABSTRACT

Abandoned, lost, or otherwise discarded fishing gear (ALDFG) poses a persistent threat to marine biodiversity and fisheries economies. İskenderun Bay in the Northeastern Mediterranean Sea, an ecologically productive and fishing-intensive region, has been increasingly affected by ghost fishing caused by ALDFG. This study aimed to (1) assess the ecological and economic impacts of ghost fishing, (2) document and retrieve ALDFG using minimally invasive methods, and (3) evaluate the cost-effectiveness of gear removal operations. Between May 2014 and April 2015, ghost nets were located and retrieved in İskenderun Bay using a combination of fishers' interviews, SCUBA, ROVs, and surface-supplied diving. Three key sites were selected for retrieval operations using a balloon lifting method. Seabed types were categorized into four habitat classes based on depth and substrate composition. In total, 565 kg of derelict fishing gear, including purse-seine and trammel nets, was successfully recovered from the survey area. Reusable and recyclable materials amounted to $5,097.72 in theoretical income, resulting in a net economic loss of $18,510. Elongation nets, especially those lost in rocky coastal areas, posed the highest environmental risk due to their persistent ghost fishing activity. This study represents the first large-scale ALDFG retrieval and economic assessment in the Northeastern Mediterranean Sea. The findings emphasize the need for systematic ALDFG monitoring, biodegradable gear use, and community-based education. Balloon-assisted lifting proved to be an effective and ecologically responsible retrieval technique. Establishing reporting mechanisms and policy frameworks is vital for mitigating ghost fishing impacts in Türkiye and similar coastal regions.

INTRODUCTION

Fisheries represent a cornerstone of global food security and economic resilience, providing livelihoods for millions worldwide (Kuczenski et al., 2022; NOAA, 2023; Stuart et al., 2024). Nevertheless, marine ecosystems are increasingly challenged by overfishing, habitat degradation, and pollution-pressures that carry significant environmental consequences (Lokrantz et al., 2009). Given their ecological diversity and productivity, aquatic environments play a critical role in supporting sustainability and must be protected to ensure both ecological integrity and human well-being. In recent years, the degradation of the physico-chemical properties of these environments has posed a serious threat to aquatic life. Although essential from an economic perspective, fishing operations can adversely impact these ecosystems in numerous ways (Gilman et al., 2021; Gilman, 2022).

Among these environmental challenges, the issue of abandoned, lost, or otherwise discarded fishing gear (ALDFG) has drawn increasing scientific and policy attention due to its long-lasting and transboundary impacts (Macfadyen et al., 2009; Stelfox et al., 2016; Drinkwin, 2022; Gallagher et al., 2023; Ssempijja et al., 2024). Fishing gear may be lost at sea due to natural forces such as storms, strong currents, or shipwrecks (Ayaz et al., 2006). In addition, operational failures-such as the improper securing of marker buoys, entanglement with marine megafauna (e.g., dolphins, whales, and seals), or damage to buoy lines caused by seabirds-can also result in gear loss (Worm et al., 2006; Liquete et al., 2013; NOAA, 2023). Furthermore, intentional human actions-such as the deliberate severing of buoy lines due to interpersonal conflicts, entanglement with previously lost gear, or mechanical failures-contribute to this growing problem (Gilman, 2015; FAO, 2016; Richardson et al., 2018, 2019; Goodman et al., 2021). Additional environmental concerns include marine tourism-related debris, stormwater-borne waste, and irregular disposal of refuse from vessels, all of which further exacerbate the problem (Savels et al., 2022).

Lost fishing nets can severely disrupt marine ecosystems by altering the sheltering and foraging behaviors of aquatic organisms and inadvertently causing the death of species such as seals, sea turtles, and seabirds. These derelict nets are often referred to as "ghost fishing" gear, as they continue to entangle and kill marine life long after being abandoned (Macfadyen et al., 2009; Jambeck et al., 2015; Gilman et al., 2016; Kim et al., 2016; Hardesty et al., 2021; Vodopia et al., 2024). The environmental impact of ghost gear varies with the type of fishing equipment; for example, gillnets and traps can continue to capture organisms for extended periods (Erzini et al., 1997; Matsuoka, 1999; Bullimore et al., 2001; Godøy et al., 2003; Nakashima & Matsuoka, 2004; Matsuoka et al., 2005; Richardson et al., 2018, 2021; Hardesty et al., 2021). Consequently, these lost devices contribute to unregulated and uncontrolled marine mortality, resulting in the loss of valuable aquatic resources, declines in biodiversity, and broader ecological degradation (Link et al., 2019).

Globally, it is estimated that approximately 6.4 million metric tons of marine debris enter the oceans annually (UNEP, 2005; Richardson et al., 2021; Kammann et al., 2023), with 8% to 12% of all fishing gear used worldwide lost at sea each year (Macfadyen et al., 2009). In Türkiye alone, an estimated 1,000 to 2,000 kilometers of fishing nets are unintentionally abandoned in marine environments annually. The scale, distribution, and consequences of ALDFG have grown markedly in recent decades, driven by the expansion of industrial fishing and the use of durable, synthetic, and buoyant materials in gear production (Macfadyen et al., 2009). The economic loss associated with lost fishing gear in Türkiye is estimated to be around 6 million $ (Taşlıel, 2008). Moreover, ghost gear contributes to substantial ecosystem damage and species mortality, with an estimated one million seabirds and over 100,000 marine mammals dying annually from entanglement (Ayaz et al., 2010; Gall & Thompson, 2015; Gray & Kennelly, 2018).

Research on ghost nets in Türkiye remains scarce, with only a limited number of studies conducted thus far-primarily in İzmir Bay (Ayaz et al., 2004) and the Karataş and Yumurtalık regions of İskenderun Bay (Taşlıel, 2008). The rich fisheries potential of İskenderun Bay has been acknowledged since the 1940s (Kosswig, 1955). The region harbors a diverse and economically valuable array of marine species.

Given the expansive nature of its fishing grounds, the unintentional loss of fishing gear presents a high risk of widespread dispersal across the seafloor. Fishers have frequently reported the accumulation of abandoned gear in the bay's natural benthic habitats, a situation exacerbated by advancing fishing technologies and increasing harvest intensity. İskenderun Bay hosts various fishing practices, including basket traps, bottom-set gillnets, trawling, and purse seining. Gear loss can result from different operational scenarios: extension nets may drift or become entangled in muddy or rocky substrates, trawl nets may be lost due to fishing errors or rope breakage-especially when buried in sediment-while purse seines are often lost when they become ensnared on rocky seabeds.

The objectives of this study were threefold: (1) to visually document the ecological impacts of lost fishing gear in the Northeastern Mediterranean Sea and to undertake the region's first underwater retrieval operations using an ecologically sensitive balloon lifting technique; (2) to estimate both the economic loss associated with ghost fishing gear and the cost of gear recovery; and (3) to develop a methodological framework that ensures diver safety and cost-efficiency, serving as a foundation for future large-scale retrieval efforts in the area.

MATERIAL AND METHODS

This study was carried out in designated fishing grounds within Northeastern Mediterranean Sea between May 2014 and April 2015. Despite notable advancements in marine survey technologies, the detection and identification of lost fishing nets remain technically challenging. Photographic documentation collected during long-term field studies highlights the detrimental effects of ghost nets on marine life and the broader the Northeastern Mediterranean Sea ecosystem. Figure 1A and 1B, taken in the Northeastern Mediterranean Sea, depict sections of a damaged trawl net entangled on a submerged wreck, with dead fish visibly trapped within the netting.

The methodological approach adopted in this research involved a combination of advanced technologies and local ecological knowledge. Initially, target areas were identified based on information obtained through interviews with local fishers. These areas were then systematically surveyed using a suite of tools, including remotely operated vehicles (ROVs), SCUBA diving, and surface-supplied diving systems (Figure 2). PVC-bodied, parachute-type lifting balloons were used during the lifting operations, each equipped with a single-dump system and a safety valve. Three balloons with capacities of 200 kg, 500 kg, and 1000 kg were employed, all manufactured from high-strength PVC material and designed to provide controlled buoyant lift with overpressure protection for safe underwater handling. In addition, a remotely operated vehicle (ROV) was utilized to support imaging and operational monitoring throughout the fieldwork. The ROV is capable of operating at depths up to 120 m, capturing 720p HD video, and is powered by a propulsion system consisting of two horizontal and one vertical thruster, allowing a maximum speed of 3 knots. With its stable imaging capability, maneuverability, and compact configuration, the ROV played a critical role in object detection, guidance, and real-time monitoring of the lifting balloon operations, thereby enhancing both the safety and efficiency of the underwater activities. Through this integrated approach, the presence, depth, and physical characteristics of abandoned fishing gear were comprehensively documented.

The fishing gear identified in the study area consisted of various types of derelict nets. These included passive gear types, such as trammel nets and cage traps, and active gear types, including purse seines. The condition of the retrieved gear was systematically assessed during diving operations, with particular attention to whether the nets were buried, overgrown with algae, or still functioning as unintended traps for marine organisms.

To support a structured analysis, the seabed environments within the study area were categorized into four distinct habitat types based on depth and substrate characteristics:

- **Type 1:** Shallow rocky and reef areas (≤ 30 meters),
- **Type 2:** Shallow seagrass-dominated areas (≤ 30 meters),
- **Type 3:** Shallow sandy and muddy areas (≤ 30 meters), and
- **Type 4:** Deeper rocky and reef areas (30–60 meters).

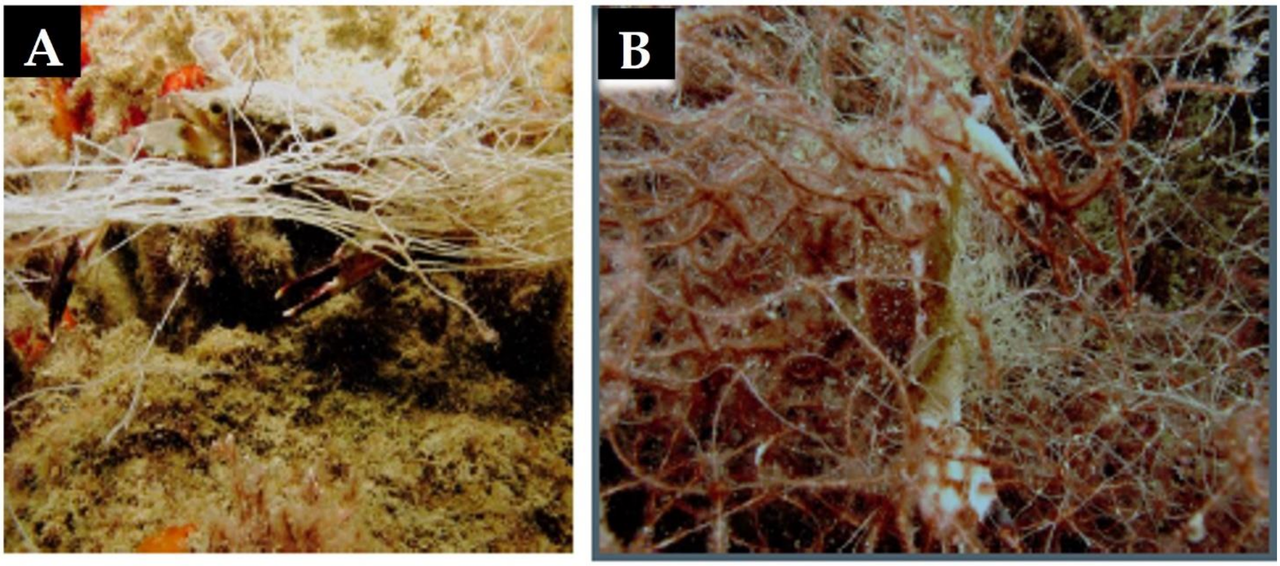

Figure 1. (A) Ghost net identified within the study sites, representing lost fishing gear persisting on the seafloor; (B) Dead fish entangled in a damaged trammel net found snagged on underwater wreckage in the Northeastern Mediterranean Sea (Photographs taken during field operations; original content).

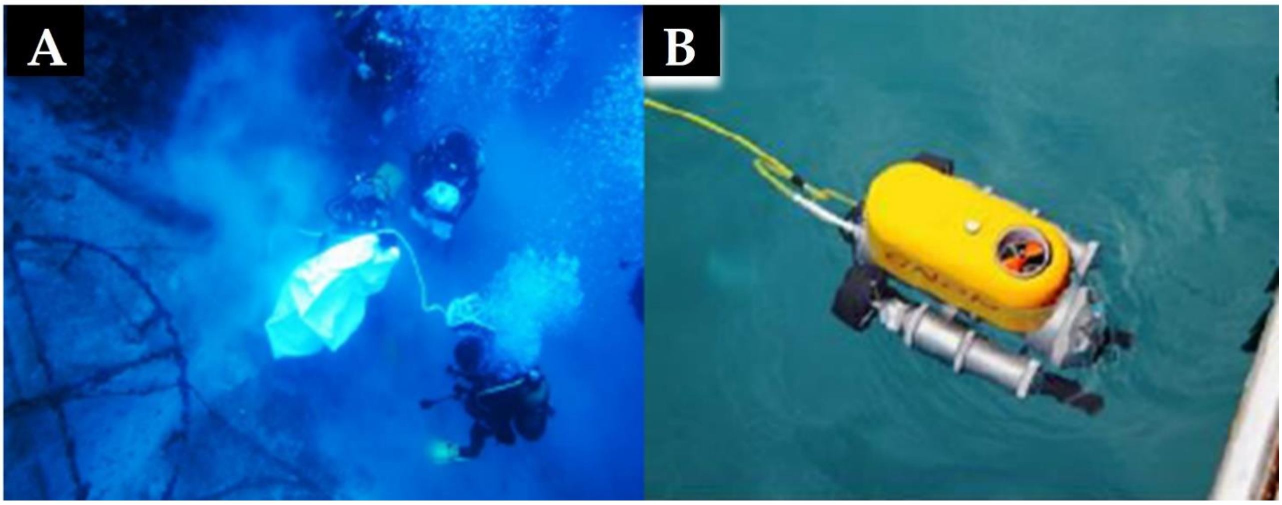

Figure 2. (A) Underwater survey operations conducted by SCUBA divers for the identification and documentation of lost fishing gear; (B) Deployment of a remotely operated vehicle (ROV) to support visual inspection and mapping of submerged ghost nets in the Northeastern Mediterranean Sea (Original field documentation).

In the second phase of the study, three sites within Northeastern Mediterranean Sea were strategically selected based on variability in seabed habitat types and depth profiles. These areas encompassed a diverse array of substrate compositions, including reef, sandy, muddy, pebbly, rocky, and vegetated bottoms. The designated locations (Figure 3) represented ecologically distinct stations across the bay. The structural heterogeneity of these benthic environments allowed for a comprehensive assessment of the spatial distribution of abandoned fishing gear, as well as an evaluation of the effectiveness and adaptability of the balloon-assisted retrieval method under varying environmental conditions (Figure 4).

In the third phase of the study, an analysis was undertaken to identify the most cost-effective method for the retrieval of lost fishing nets from the selected locations. The fourth phase expanded the scope to a comprehensive economic assessment of ghost gear and its associated impacts. From an economic perspective, two principal components were evaluated: (1) the financial loss incurred by fishers as a result of gear loss, and (2) the operational costs involved in locating and retrieving derelict nets from the seafloor. For the purposes of this analysis, "net materials" were defined to include all structural components of the gear, such as netting fabric, ropes, lead sinkers, and floaters. Total economic losses and recovery expenditures were estimated using up-to-date market prices, providing a realistic quantification of the financial burden that ghost fishing imposes on both individual stakeholders and the fisheries sector as a whole.

Figure 3. Map of the study area extending between Konacık and Keldağ in the Northeastern Mediterranean Sea, indicating the locations-marked with solid red circles-where ghost nets were identified and retrieved during field surveys (Geospatial data compiled from dive operations and remote sensing tools) (1)Keldağ-Uzunkaya, (2)Keldağ-Doğruca Burnu, and (3)Konacık-Kale (Modified from Özyılmaz et al., 2024).

Figure 4. Retrieval of lost fishing nets from the seafloor using the balloon lifting method, a technique designed to minimize disturbance to sensitive benthic habitats while enabling the safe extraction of ghost gear to the water surface (Original documentation from field operations).

The economic loss associated with ghost fishing can be formulated as follows:

- **Economic Loss** = ***Cost of acquiring new fishing gear*** (i.e., expenses incurred by fishers to replace lost nets and continue their operations) **+** ***Net removal costs*** (i.e., labor costs + additional operational costs)
- **Economic Income** = ***Reusable materials*** (e.g., lead weights, floaters) **+** ***Recyclable materials*** (e.g., nets, ropes)
- **Total Expense** = ***Economic Loss – Economic Income***

For future research, a more comprehensive cost or cost-effectiveness analysis would benefit from expanded data collection. This should encompass not only the direct expenditures related to gear loss and recovery operations but also potential economic gains from ongoing fishing activities and alternative revenue streams-such as the resale or recycling of retrieved materials-arising from implemented mitigation strategies.

RESULTS

The approach adopted in this study aimed to assess the impact of lost fishing nets across different seabed habitats and to facilitate their removal from the marine environment. Sampling operations were conducted at three locations: Keldağ-Uzunkaya, Keldağ-Doğruca Burnu, and Konacık-Kale. Several ghost nets were identified and successfully retrieved from these sites. Specifically, a 55 kg elongation net was removed from a depth of 35 meters at Keldağ-Uzunkaya, a 400 kg purse seine net was extracted from 40 meters at Keldağ-Doğruca Cape, and a 110 kg purse seine net was retrieved from 45 meters at Konacık-Kale.

Analysis of the collected data indicated that *tongue elongation nets* accounted for the highest proportion of lost gear in the area, followed by *shrimp nets* and other elongation net types. In the Keldağ region in particular, the greatest losses occurred among elongation nets deployed parallel to rocky coastal zones, locally referred to as "big eye" or "rubble" areas. These findings suggest that shrimp and tongue elongation nets-given their structural characteristics, shallow deployment depths, and exposure to strong currents and storms-are less likely to maintain their physical integrity over time. However, when these nets become entangled in rocky substrates, they are less likely to be displaced or degraded, thereby posing a long-term environmental hazard.

Various types of traps were also encountered in the study area. These traps-targeting species such as grouper, sea bream, and coral-are typically deployed in rocky habitats using sardine-like bait. The loss of such gear, particularly due to adverse weather conditions, can lead to uncontrolled fish mortality, exacerbating the ecological consequences of ghost fishing.

The direct cost associated with the retrieval of ghost nets was calculated at $6,970 (Table 1). This estimate excluded expenditures related to balloon lift systems, underwater imaging equipment, and tubing materials, which were not covered within the scope of the project. Moreover, labor costs were largely assumed by the research team, further reducing overall project expenses. The estimated economic income of $5,097.72 (Table 2 and Table 3) represents a theoretical valuation of the reusable and recyclable components recovered from the retrieved nets. In contrast, the $14,060 figure reflects a hypothetical cost for fishers to replace the lost nets with new gear. These figures culminate in a total economic loss estimate of $18,510 (Table 4), representing the projected financial burden to the national economy attributable to ghost gear in the region.

This study also highlighted that elongation nets-particularly those continuing to capture marine organisms' post-loss-pose the highest ecological risk among all identified gear types.

Table 1. Work breakdown and cost analysis ($) for diving operations conducted at selected ghost net retrieval locations in the Northeastern Mediterranean Sea

Location	Work Breakdown and Costs				Grand Total ($)
	Diver's wage*	Superior wage**	Boat rental	Subsistence (Viaticum)	
Keldağ-Uzunkaya (2 days, 5 divers, 1 superior)	1600	400	900	90	**2990**
Keldağ-Doğruca (1 day, 5 divers,1 superior)	800	200	900	90	**1990**
Konacık-Kale (1 day, 5 divers, 1 superior)	800	200	900	90	**1990**
Total cost ($)	**3200**	**800**	**2700**	**270**	**6970**

Note: *Diver wage (person/day) = 160 $. **Superior wage (person/day) = 200 $.

Table 2. Quantity and estimated economic value ($) of reusable and recyclable materials-such as nets, lead sinkers, floats, and ropes-retrieved from ghost fishing gear at different locations in the Northeastern Mediterranean Sea

Location	Fishing Gear Type	Extracted Net Weight (kg)	Net (kg)	Lead (kg)	Float (pcs)	Rope (kg)
Keldağ-Uzunkaya	Trammel Net	55	7.3	31.84	289	4.34
Keldağ-Doğruca	Purse Seine	400	394	6	0	0
Konacık-Kale	Purse Seine	110	97	13	0	0
Total		**565**	**498.3**	**50.84**	**289**	**4.34**

Table 3. Unit prices and total estimated economic value

Material	Unit Price ($)	Total Quantity	Estimated Value ($)
Net (kg)	10	498.3	4983
Lead (kg)	0.5	50.84	25.42
Float (pcs)	0.3	289	86.7
Rope (kg)	0.6	4.34	2.6
Total			**5097.72**

Table 4. Estimated costs ($) associated with operational activities conducted during the study

Description	**Amount ($)**
Fishnets Removal Cost	6970
New Mesh Cost	14060
Total Economic Loss (Removal + New Mesh Cost)	21030
Economic Income	2520
Total Expense	**18510**

The most effective strategy for mitigating ghost fishing is to implement preventative measures that directly address the root causes of fishing gear loss. These efforts should be embedded within a broader framework of integrated coastal zone management and sustainable fisheries governance. One such innovation developed by the fisheries sector involves time-release mechanisms, which are engineered to deploy small surface buoys at preset intervals. These buoys assist in the relocation and retrieval of lost gear, thereby reducing the likelihood of long-term ghost fishing.

In the context of trap fishing, similar systems are employed to link the trap entrance to an escape hatch, which opens automatically after a predetermined period, allowing any captured organisms to escape and rendering the gear inoperative. In Türkiye, multi-panel nets often remain deployed for extended durations, increasing the risk of loss. To minimize these risks, it is essential that the location of deployed fishing gear is clearly marked and visible to other fishers. For example, during nighttime fishing, equipping net buoys with lights can help prevent overlap and potential gear conflict, thereby reducing unintentional losses.

Complementary to technological solutions, comprehensive studies aimed at quantifying the extent and identifying the causes of gear loss in commercial fisheries are critical. Such data are vital for evaluating the magnitude and ecological impact of ghost fishing. In line with regulatory compliance, all ghost nets and fishing gear recovered during this study were formally transferred to the Hatay Provincial Directorate of Agriculture and Forestry, Department of Fisheries, in accordance with the provisions of Fisheries Law No. 1380.

DISCUSSION

This study offers critical insights into the ecological and economic consequences of ghost fishing caused by abandoned, lost, or otherwise discarded fishing gear (ALDFG) across various benthic habitats in the Northeastern Mediterranean Sea. The successful identification and recovery of ghost nets from diverse seafloor types-including rocky reefs, sandy substrates, and seagrass meadows-underscores the widespread and pressing nature of the problem. The findings emphasize the necessity for integrated, habitat-sensitive fisheries management strategies. Notably, elongation nets, particularly those deployed in shallow rocky coastal areas, emerged as the most frequently lost gear type and the greatest ecological threat due to their prolonged capacity to entangle marine life. These results are consistent with global research highlighting the persistent ecological risks associated with passive fishing gear once abandoned (Macfadyen et al., 2009; Gilman et al., 2016; Gajanur & Jaafar, 2022).

Although ALDFG is a recognized concern in marine ecosystems, its full ecological footprint remains underexplored (Wasave et al., 2025). In Türkiye, scientific investigations on ghost fishing have thus far been limited to localized studies in areas such as İzmir Bay (Ayaz et al., 2004), the Sea of Marmara (Uçar & Öztekin, 2023), the Gökova Special Environmental Protection Area (Ayaz et al., 2010), and specific locations in İskenderun Bay (Taşlıel, 2008). These prior efforts largely focused on quantifying lost gear and identifying contributing factors. He & Suuronen (2018) suggests that appropriate gear marking technologies effectively help identify ALDFG sources, track entangled gear on marine organisms, and reduce marine litter. The present study expands upon this foundation by offering a comprehensive assessment of ghost net locations, gear types, and associated economic costs. As the most productive fishing ground in the Eastern Mediterranean, İskenderun Bay supports a broad array of fishing activities, including trawling, purse seining, gillnetting, longlining, and trap fishing. Interviews with local fishers confirmed that gear loss is common, driven by both environmental pressures (e.g., storms, strong currents) and operational constraints (e.g., gear overlap). Extensive field surveys involving SCUBA and ROV-based inspections confirmed the presence of ghost nets across varying depths. To mitigate further ecological damage during retrieval, an environmentally sensitive balloon-assisted recovery technique was employed, marking a notable methodological advancement over conventional gear removal approaches.

This study builds on earlier estimates by Taşlıel (2008) by not only quantifying seasonal gear loss in Karataş and Yumurtalık but also by documenting gear classification, spatial distribution, and retrieval costs. Consequently, this work provides a more holistic understanding of the ghost fishing issue in the region and serves as a scientific foundation for future policy formulation and sustainable fisheries practices.

Extensive national and international research has documented the scale and consequences of ghost fishing. For instance, during the 2006-2007 season, a total of 1,856 nets-including shrimp gillnets and standard gillnets-were reported lost along Istanbul's coastline, with an estimated combined length of 226 kilometers (Yıldız & Karakulak, 2010). Uçar & Öztekin (2023) reported that purse seines constituted 60% of lost gear, followed by gillnets (29%) and bottom-set nets (6%). Historical data indicate that along the Istanbul coast alone, approximately 229.5 km of gillnets, 2.7 km of fishing lines, and 14 traps were lost in 2008, with turbot nets representing the highest proportion. Similar patterns were observed by Samsun (2004), who documented the recurring loss of turbot nets in the Black Sea due to retrieval difficulties.

Ayaz et al. (2004) reported the loss of 200-280 km of gillnets in İzmir Bay in 2002, primarily due to entanglement, adverse weather, and insufficient gear marking. International studies support these trends. For example, lost gillnets in Norwegian waters were found to entangle valuable species such as plaice, while Godøy et al. (2003) observed high mortality rates in ghost crab traps in the Barents Sea, where recovered traps often contained dead crabs or skeletal remains. Similar results were seen in İskenderun Bay, where recovered ghost traps contained both deceased and decomposing marine organisms.

This study further demonstrates that, in addition to gillnets and trammel nets, diverse trap configurations-such as fyke nets-substantially contribute to ghost fishing in the region. Because passive gear is inherently designed to capture marine life even when unattended, its loss represents a persistent ecological hazard (Gilman, 2015). Once lost, such gear can remain active for extended periods, continuing to trap marine organisms until it is either retrieved or naturally degraded-a process that can span several years depending on environmental conditions (Miller, 1990). This long-term entrapment exacerbates the depletion of marine resources and degradation of benthic habitats.

Trammel net fishing in İskenderun Bay occurs year-round and is prevalent in small-scale fisheries. Seasonal depth ranges vary, with operations typically taking place between 10–60 meters from December to May and between 60-125 meters from May to November. According to small-scale fisheries data, approximately 227 vessels engage in trammel net fishing in the region. Their distribution spans Karataş (82), Yumurtalık (47), Gölovası (43), Dörtyol (13), İskenderun (21), Arsuz (14), and Çevlik (7) (Özyurt et al., 2008).

Species composition also influences ghost fishing dynamics. Carr et al. (1992) observed that although net efficiency declines rapidly, the capture rate of crustaceans such as shrimp may actually increase, even in deteriorated gear. The duration of gear functionality is largely influenced by environmental conditions and seabed structure. Studies by Matsuoka et al. (2005) and Nakashima & Matsuoka (2004) found that gear entangled in rocky or reef habitats tends to retain its three-dimensional form for longer periods, enabling prolonged ghost fishing activity.

The mechanical disturbance caused by trawling also contributes to habitat degradation. Jennings & Polunin (1996) noted that trawl doors suspend sediment and generate turbulence that directs fish into nets. The adverse impacts of ghost fishing gear encompass significant environmental damage, such as continued unintended catches and habitat degradation, as well as substantial economic costs, including clean-up efforts and reduced fishery productivity (Macfadyen et al., 2009). Continued mortality caused by lost nets and traps depletes fish stocks and results in unrecorded economic losses. Although the finite nature of marine resources has been recognized since the 1960s (Bingel, 2002), the mortality caused by ghost gear remains largely invisible to stock assessments and economic planning, thereby undermining sustainability goals.

This study holistically evaluated both the environmental impacts of ALDFG and the economic costs associated with gear loss and recovery. Comparable research by McIntyre et al. (2023) in Southwest Nova Scotia revealed that abandoned lobster traps continued to affect biodiversity and fishing productivity long after their loss. The findings of the present study are consistent with these observations and further underscore the multifaceted risks posed by ghost fishing.

The use of ROV technologies and SCUBA in this study aligns with monitoring protocols reported by Liu et al. (2023) in Taiwan's Penghu Islands. The balloon-assisted lifting technique used for gear recovery proved to be a low-impact and ecologically sound alternative, paralleling best practices employed by Royer et al. (2023) in the Hawaiian Islands and Palmyra Atoll.

Community engagement was also central to the present study. Collaboration with local fishers and the promotion of awareness campaigns reflect participatory strategies endorsed by Mengo et al. (2023), who highlighted the importance of local ecological knowledge in designing effective mitigation measures. Furthermore, the study supports the use of biodegradable fishing gear as a long-term solution to ghost fishing, echoing findings from Drakeford et al. (2023), who demonstrated its economic and ecological feasibility in the English Channel.

Finally, addressing ALDFG requires international coordination. Liu et al. (2024) emphasized the importance of trilateral cooperation in the Sulu-Sulawesi Seas, supporting the present study's recommendation to develop cross-border reporting systems and collaborative management frameworks. As ghost fishing is a transboundary issue, only harmonized regional responses will yield sustainable outcomes.

CONCLUSION

This study presents one of the first comprehensive assessments of the ecological and economic impacts of abandoned, lost, or otherwise discarded fishing gear (ALDFG) in the Northeastern Mediterranean Sea. Through the use of ecologically sensitive methods-such as balloon-assisted retrieval-and an interdisciplinary approach integrating field surveys, diver observations, and economic evaluation, the study reveals the magnitude and complexity of the ghost fishing problem in the region. The findings demonstrate that elongation nets, particularly those lost in shallow rocky areas, pose the highest ecological risk due to their prolonged entanglement potential. The recovery of over 565 kg of fishing nets and associated components underscores the persistence of ghost gear and its capacity to continue inflicting environmental damage long after abandonment. In economic terms, the retrieval and replacement costs amounted to $21,030, while the potential recovery income from recyclable materials remained significantly lower, at $5,097.72-resulting in a net loss of $18,510 to the regional fisheries sector. The study also highlights the operational challenges and risks involved in ghost net removal. The success of the balloon lifting method illustrates the feasibility of low-impact gear retrieval in sensitive benthic environments, yet also calls attention to the need for professional safety protocols and pre-removal habitat assessments. Importantly, the research emphasizes that technical interventions alone are insufficient. Reducing the incidence of ALDFG requires a multifaceted strategy, including:

- The promotion of biodegradable fishing gear,
- The implementation of gear marking and tracking technologies,
- The design of habitat-specific recovery protocols, and
- The active involvement of local fishing communities through education and awareness campaigns.

Finally, the findings underline the importance of establishing national and regional frameworks for systematic ALDFG monitoring, reporting, and response. Given the transboundary nature of marine debris, Türkiye's engagement in cooperative Mediterranean-wide initiatives will be critical in addressing the ghost fishing problem at scale.

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Compliance with Ethical Standards

Authors' Contributions

YM : Writing – review & editing, Supervision, Investigation, Data analysis, Conceptualization.

MFC : Data analysis, Writing – original draft, Investigation.

ABB : Sampling, Investigation.

AD : Sampling, Writing – review & editing, Investigation, Data analysis.

MG : Sampling.

EŞ : Sampling, Writing – review & editing, Investigation.

MS : Sampling, Investigation.

NU : Sampling, Investigation.

All authors read and approved the final manuscript.

In Memoriam: Dr. Mevlüt Gürlek

This publication is dedicated to the memory of Dr. Mevlüt Gürlek, whose profound dedication to marine science and invaluable contributions significantly shaped the course of this research. Dr. Gürlek's scientific insight, collegial spirit, and unwavering enthusiasm for the marine environment left a lasting impact on this project and on all who had the privilege of working with him. Although he is no longer with us, his legacy endures through the continued pursuit of scientific knowledge he so passionately championed. He is remembered with deep respect and sincere gratitude.

Conflict of Interest

The authors declare that there is no conflict of interest.

Ethical Approval

For this type of study, formal consent is not required.

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Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

AI Disclosure

The authors confirm that no generative AI was used in writing this manuscript or creating images, tables, or graphics.

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Effect of Spraying Sulfur and Inoculation Rhizobacteria on Growth and Yield of Canola

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ABSTRACT

Due to the increasing importance of using environmentally friendly methods to increase the yield of crops, two- year experiment carried out in a field located in the Dehgolan region, in the northwest of Iran, to study influence of sulfur spraying and plant growth promoting rhizobacteria inoculation on canola traits. The experiment was arranged as a split-plot factorial arrangement based on randomized complete block design with three replications. The main plots included two levels of sulfur (control and application), and the factorial combinations of strigolactone (control and application) and microorganisms (control, *Funneliformis mosseae*, *Bacillus lentus*, *Pseudomonas fluorescens*, *Thiobacillus* sp.) were allocated to the sub-plots. The results of combined analysis showed that the 1000 seed weights and seed yield increased significantly by sulfur application. At the same time, the 1000 seed weights decreased under the influence of strigolactone. Also, the SPAD number, the number of pods and seeds per plant, the 1000 seed weights and the seed yield increased significantly by influence of microorganisms, especially *Thiobacillus*, compared to control treatment. Based on the results of interaction effects, all traits except the number of SPAD were affected by the interaction effect of sulfur, strigolactone and microorganisms. The application of sulfur along with strigolactone and *Thiobacillus* significantly increased the number of pods per plant (200), the 1000 seed weights (4.53 g) and the seed yield (2552 kg/ha).

INTRODUCTION

Sulfur (S) is very important for achieving maximum yield in canola (Shoja et al., 2018). Therefore, in recent years, various researches have been conducted to determine the optimum amount of sulfur required by this crop. It has been demonstrated that sulfur has a significant effect on the foundation of fatty acid in oilseed crops such as soybean, canola, and groundnuts (Karaaslan et al., 2020). There is greater synergistic influence of sulfur on growth factor, yield and yield attributes, nutrient uptake, protein and oil production in canola (Asadi Rahmani et al., 2018). Sulfur fertilizers have become a main part of the fertilizer mix for canola growers. Sulfur compounds inhibit the growth and activity of mycorrhizal mycelium on the root (Gryndler et al., 1998).

Mycorrhizal fungi are capable of colonizing most of the world's crop plants (95% of the current species of crops belong to families that are mycorrhizal). Many profits accrue to crops from their relationship with arbuscular mycorrhizal fungi (AMF) (Mitra et al., 2019). Mycorrhizal could improve water uptake and nutrient absorption, especially phosphor (Begum et al., 2019). Some plant families, such as *Brassicaceae, Chenopodiaceae* and *Amaranthaceae*are unable to establish symbiosis with mycorrhizal fungi or have partial symbiosis. (Singh et al., 2003). Canola (*Brassica napus* L.) is one of the important oilseed crops in Iran, which is cultivated in rotation with wheat. It ranks tertiary because of world oilseed yield after *Glycine max* and *Arachis hypogaea* (Mohammadi et al., 2012). Poor or no mycorrhizal associations in this family attributed to specific anatomical structures of roots and non-germination of arbuscular mycorrhizal spores due to allelopathic compounds leakage such as glucosinolates, isothiocyanates (Schreiner & Koide, 1993) or defenses, which suppresses activities of pathogenic fungi (Choi et al., 2009). Mukherjee & Ane (2011) found root architecture change and gene expression of symbiotic in crops due to exudates of germinating spores from *Glomus* species.

Supplement effects of arbuscular mycorrhizal fungi well known on the phosphate solubilizing bacteria activity (PSB). Nacoon et al. (2020) showed that beneficial effects of co-inoculation of a PSB strain and AMF, when mixed with addition of rock phosphate, to improve the growth. Some PSB play a role in siderophore production (Hamadali et al., 2008), Secretion of plant hormones includes auxin and gibberellins (Souchie et al., 2007), antibiotics releases (Taurian et al., 2010) and production of secondary metabolites (Yang et al., 2008).

Strigolactones hormones adjust plant growth and development (Yoneyama & Brewer, 2021), enhance seed germination and primary root length and also nodule formation (Mitra et al., 2019). They are derived from carotenoids, which are rich sources of biologically active compounds. Known role of strigolactones is stimulating arbuscular mycorrhizal fungi colonization and promoting of symbiosis with root nodule bacteria (Yoneyama, 2020). Strigolactones help plants confront some kinds of stresses via drought, salinity, heavy metal, nutrient starvation, and heat (Alvi et al., 2022).

However, despite extensive research on the individual effects of sulfur, arbuscular mycorrhizal fungi, phosphate-solubilizing bacteria, and strigolactones on canola growth and yield, the combined impact of these factors remains unclear. Therefore, the present study aims to investigate the synergistic effects of sulfur fertilization, strigolactone application, and AMF inoculation alongside PSB on canola growth, nutrient uptake, and overall yield.

MATERIAL AND METHODS

Experimental Details

The study was conducted in a field located in the Dehgolan region (35.2818° N, 47.4196° E), in the northwest of Iran, over the course of two growing seasons. Figure 1 illustrates the monthly rainfall and temperature data for the years 2020 and 2021 (January to December).

The experimental design followed a split-plot factorial arrangement within a randomized complete block design, with three replications. Sulfur application was assigned to the main plots, while the sub-plot factors included microorganisms (control, *Funneliformis mosseae*, *Bacillus lentus*, *Pseudomonas fluorescens*, and *Thiobacillus* sp.) and strigolactone treatments (seed priming and control). Each sub-plot measured 5 meters in length and consisted of five rows, spaced 1 meter apart. A 2-meter buffer zone was maintained between the main plots to mitigate the effects of lateral water flow and movement during spraying.

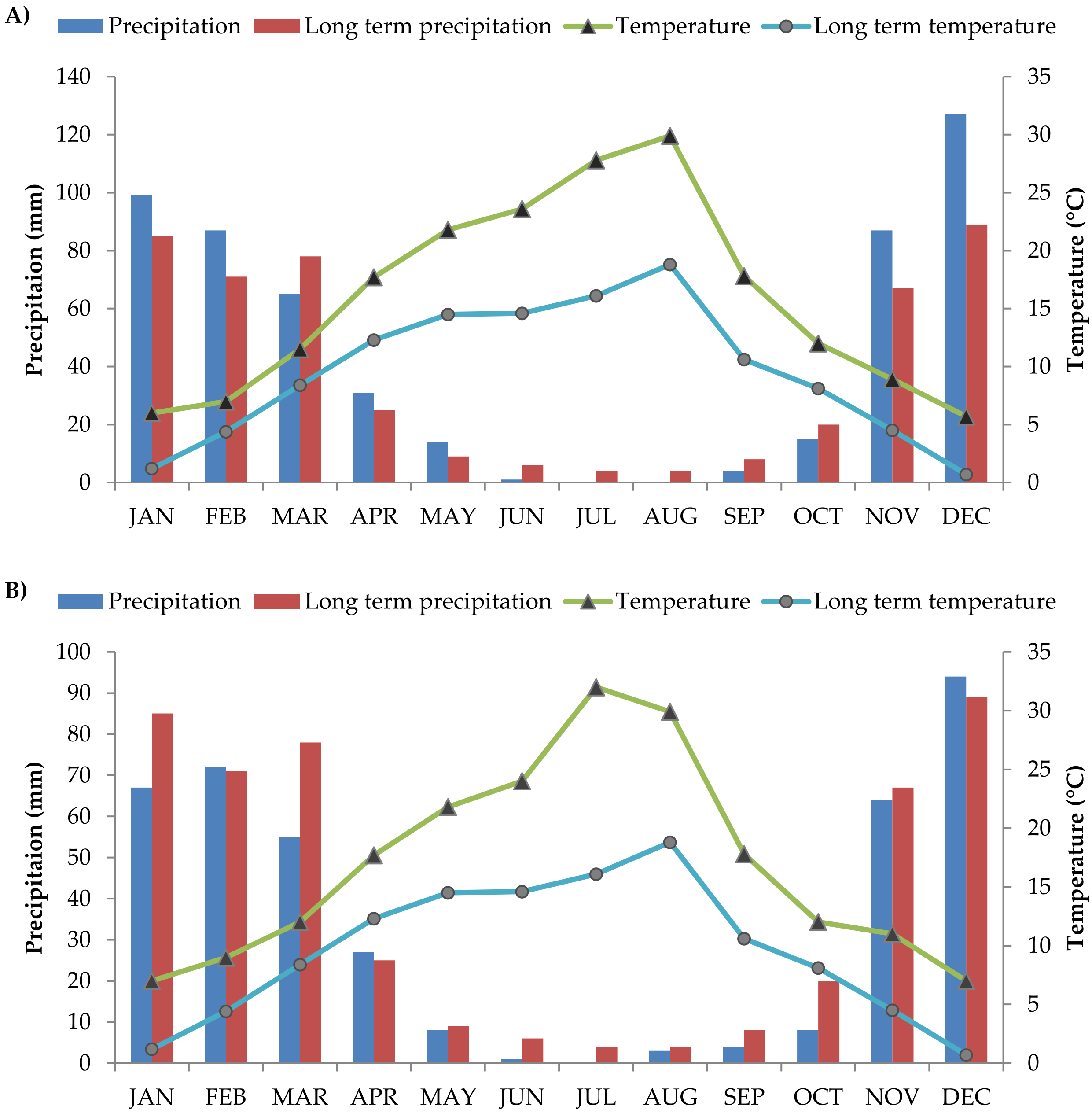

Figure 1. Monthly precipitation and air temperature from January to December for the years 2020 (A) and 2021 (B), along with the long-term average (1980-2020), in Dehgolan, Iran.

The AMF inoculum consisted of soil particles, fungal spores (30,000 spores per 20 ml inoculum), infected root fragments, and hyphae derived from a stock culture of *F. mosseae* with a single subtending hypha. The sporocarps, which contained 2-5 spores enclosed in a peridium, were produced on host plants at the Iranian Soil and Water Research Institute. Mycorrhizal fungal spores were cultured in pots filled with sandy soil (autoclaved at 121°C for 30 minutes, repeated three times) in a greenhouse maintained at 25°C during the day and 16°C at night, with a 16-hour light/8-hour dark photoperiod and a relative humidity of 60-65%. The AMF inoculum was placed 5 cm beneath the canola seeds during sowing.

The phosphate-solubilizing bacteria used in this study were *B. lentus* (P5 strain, lecithinase-negative, gram-positive, peritrichous flagella, ellipsoidal shape, paracentral spore, slightly curved rods) and *P. fluorescens* (S153 strain, gram-negative, rod-shaped, multiple flagella, and obligate aerobes). These strains were isolated and identified at the Soil and Water Research Institute, Iran. Phenotypic characterization was performed using the API system, while phylogenetic identification was conducted through sequence analysis of the 16S rRNA gene. Bacterial strains were extracted and evaluated from soil samples gathered throughout various locations in Kurdistan, Iran. Before inoculation, the bacteria were revived and grown in a nutrient medium. They were grown on a shaker at 37°C and 180 rpm. Afterward, the culture was centrifuged at 10,000 rpm for 15 minutes and washed with 0.9% sodium chloride. The bacterial pellet was then re-suspended in a sterile phosphate buffer (López-Valdez et al., 2011) to achieve a final density of approximately 40×10^6 CFU/cm^3. The selected isolates were subsequently inoculated into the same medium and incubated at 30°C for 10 days. The phosphate-solubilizing bacteria (PSB) were applied 5 cm below the canola seeds during sowing.

To evaluate the effectiveness and persistence of the inoculation, the approach described by Burr (1984) was utilized 30 days following sowing. *Thiobacillus* inoculants were prepared using Postgate culture medium, as outlined by Vishniac & Santer (1975). Once the culture media were ready, the selected bacterial strains were multiplied with the aid of a perlite-based carrier. A total of one kilogram of inoculant was generated and stored in suitable plastic containers, ensuring bacterial viability at temperatures ranging from 4°C to 15°C. All procedures were conducted in shaded areas, away from direct sunlight. The *Thiobacillus* inoculum was placed 5 cm below the canola seeds during planting. Soil samples (0-30 cm depth) were collected before sowing to assess the physicochemical properties (Table 1). In these soil samples, pH was measured in a 1:2.5 (w/v) soil-to-water extract. Total nitrogen (N) was determined using the Kjeldahl method (Bremner & Mulvaney, 1982), while soil Olsen-P content was measured by extracting with 0.5 mol/L $NaHCO_3$ followed by Mo-Sb colorimetry (Olsen & Sommers, 1982).

Available potassium (K) was extracted using varying concentrations of NH_4OAc, including 0.1, 0.25, 0.5, and 1 M. The potassium content in the ammonium acetate extracts was measured using atomic absorption spectrometry (Warncke & Brown, 2011).

Prior to sowing, 100 kg of nitrogen (N)/ha as urea and 75 kg of phosphorus (P_2O_5)/ha as superphosphate were applied during plowing. Additionally, 100 kg of nitrogen (N)/ha was applied as a top dressing during early to mid-flowering. Canola seeds were sown at a density of 80 plants per m^2 on September 16 and 25 for the first and second years, respectively. Pest and weed control measures were implemented throughout the growing season.

Crop Traits Measurement

At the flowering stage, chlorophyll content was measured using a handheld dual-wavelength meter (SPAD-502 Plus). Measurements were taken midway along the uppermost leaf of six randomly selected plants located within the central area of three rows in each plot. At the ripening stage, samples were collected from different plots to measure seed yield and yield components. To avoid potential border effects, three central rows from each plot were sampled. The seeds were manually separated and cleaned. Moisture content was measured using the gravimetric method by drying the samples at 105°C for 24 hours, and the results were standardized to 12% moisture. From the harvested plants, five plants were randomly selected, and the following characteristics were measured: the number of pods per plant, the number of seeds per pod, and the weight of 1000 seeds.

Table 1. Physic-chemical characters of soil analysis in the field of study

Year	Silt %	Sand %	Clay %	Soil Texture	pH	EC (ds/m)	SOC %	Available N (mg/kg)	Available P (mg/kg)	Available K (mg/kg)
2020	26	39.8	34.2	Clay loam	7.36	1.21	1.13	0.022	5.3	277
2021	22	42.8	35.2	Clay loam	7.34	1.18	0.68	0.025	6.2	284

Statistical Analyses

After verifying the homogeneity of variances using Bartlett's test, a combined analysis of variance was performed using the SAS 9.4 statistical software. The least significant difference (LSD) test was applied to compare the means of the traits, with a significance level set at $p<0.05$.

RESULTS

The SPAD number, which is an indicator of greenness in plants, became significant under the influence of microorganisms' inoculation at the level of 1% and interaction of microorganism and strigolactone at 5%. In this study microorganism had positive effects on SPAD, as *Thiobacillus* inoculation achieved the maximum SPAD (Table 2).

Also, the pod number per plant significantly affected by year, microorganism, and also some double and triple interaction effects. The effects of microorganisms on the number of pods per plant were effective so that, the maximum number of pods was recorded in the *Thiobacillus* treatment (Table 2). The positive effect of microorganisms in increasing the number of pods per plant was in *Thiobacillus* (4.89%), *Pseudomonas* (3.51%), *Bacillus* (3.1%) and *F. mosseae* (1.96%) compared to control. Triple interaction effect showed that the highest number of pods per plant was recorded by strigolactone application and sulfur foliar spraying and *Thiobacillus* inoculation (Figure 2).

Also seed number per pod affected significantly by microorganism, interaction of strigolactone and microorganism, and also sulfur, strigolactone and microorganism interactions. Numbers of seed per pod reached maximum by no sulfur, no strigolactone and only by *Thiobacillus* inoculation (Figure 3). The number of seeds per pod improved in *Thiobacillus* (5.25%), *Pseudomonas* (0.89%) and *Bacillus* (0.28%) compared to control (Table 2). Also seed weights were affected by main effects and interaction, as seen, the highest seed weight was found by sulfur, strigolactone and *Thiobacillus* inoculation (Figure 4).

Seed weight increased by 12.78% under the influence of sulfur application and decreased by 0.71% under the influence of strigolactone. It seems that the positive effect of strigolactone has led to an increase in the number of pods in the plant. The seed weight enhanced by *Thiobacillus* (1.94%), *Pseudomonas* (0.24%), *Bacillus* (0.97%) and *F. mosseae* (1.94%) compared to control (Table 2).

Based on the two-year results of this experiment, it can be seen that the canola seed yield significantly affected by sulfur and interaction effects of sulfur, strigolactone and microorganism. As shown the seed yield enhanced by 23.22% by sulfur application compared to the control (Table 2). The effect of microorganisms on the canola yield showed that the maximum canola yield achieved by *Thiobacillus* (Table 2). In this study, seed yield enhanced up to 243 kg/ha by microorganisms. The seed yield also improved by *Thiobacillus*, *Pseudomonas*, *Bacillus* and *F. mosseae* as: 12.55, 4.82, 4.44 and 3.96%, as arrangement, compared to control.

Table 2. Influence of sulfur spraying and microorganism's inoculation on canola yield and yield components

Treatment	Method	SPAD number	Pod number per plant	Seed numbers per pod	1000×Seed weight	Seed Yield (kg/ha)
Sulfur spraying	No (Control)	35.86 a	163.55 a	28.58 a	3.91 b	1829.62 b
	Spraying	39.36 a	184.08 a	27.71 a	4.41 a	2254.5 a
Strigolactone priming	No (Control)	37.51 a	168.45 a	28.7 a	4.18 a	2019.42 a
	Priming	37.71 a	179.18 a	27.6 a	4.15 b	2064.7 a
Microorganisms	No inoculation (Control)	35.7 c	169.25 d	27.79 b	4.12 b	1941.91 c
	Funneliformis mosseae	38 b	172.58 c	27.79 b	4.2 a	2018.88 b
	Bacillus lentus	37.25 b	174.5 b	27.87 b	4.16 ab	2028.2 b
	Pseudomonas fluorescens	37.58 b	175.2 b	28.04 b	4.13 b	2035.7 b
	Thiobacillus sp.	39.54 a	177.54 a	29.25 a	4.2 a	2185.63 a

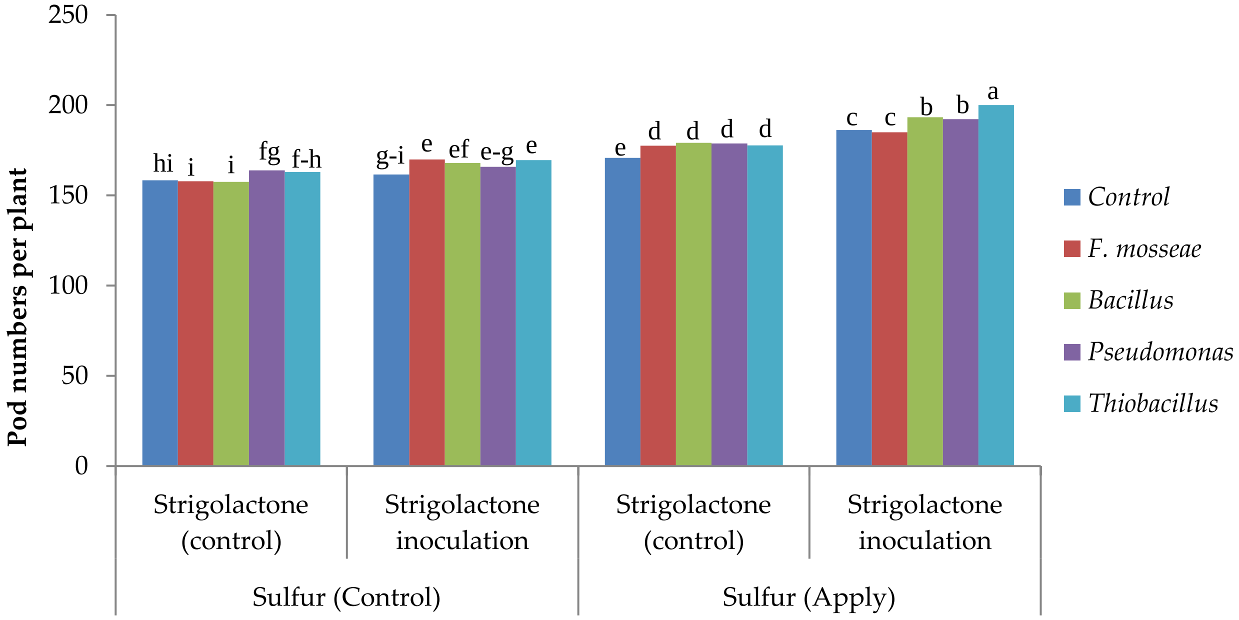

Figure 2. The interaction effect of sulfur spraying and plant growth promoting rhizobacteria inoculation on pod numbers per plant

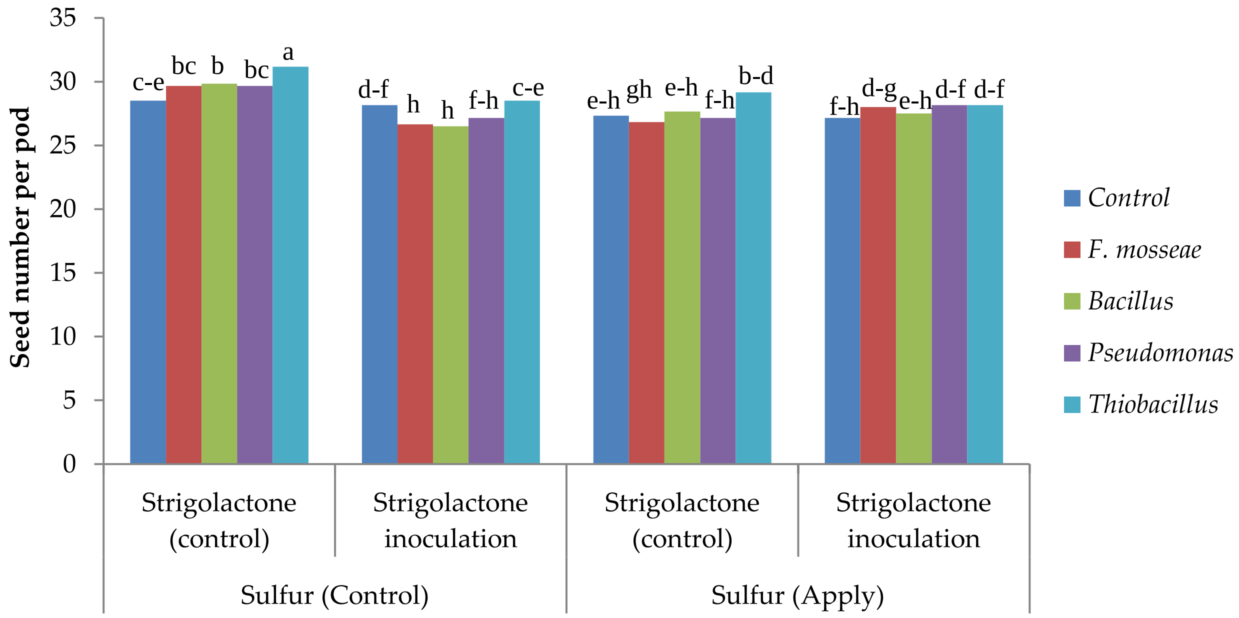

Figure 3. The interaction effect of sulfur spraying and plant growth promoting rhizobacteria inoculation on seed numbers per pod

Also, based on the triple interaction effect of sulfur, microorganisms and strigolactone, a surprising increase of 47% in canola seed yield was observed under the influence of sulfur and strigolactone, and *Thiobacillus* inoculation (Figure 5).

DISCUSSION

Positive but different effects of experimental treatments were observed on greenness index, yield components and canola seed yield as one of the important oilseed plants. Increasing photosynthetic pigments by biofertilizers such as *Bacillus subtilis* and *Pseudomonas fluorescens* inoculation were found by other researchers (Mohamed & Gomaa, 2012). Also, photosynthetic efficiency enhanced by mycorrhizal fungi *F. mosseae* (Begum et al., 2019). Improved leaf chlorophyll index by *Pseudomonas fluorescens* in canola reported by other researchers (Kazemi Oskuei et al., 2023). These researchers attributed the increase in chlorophyll to the improvement of nutrients uptake such as nitrogen, phosphorus, potassium and iron.

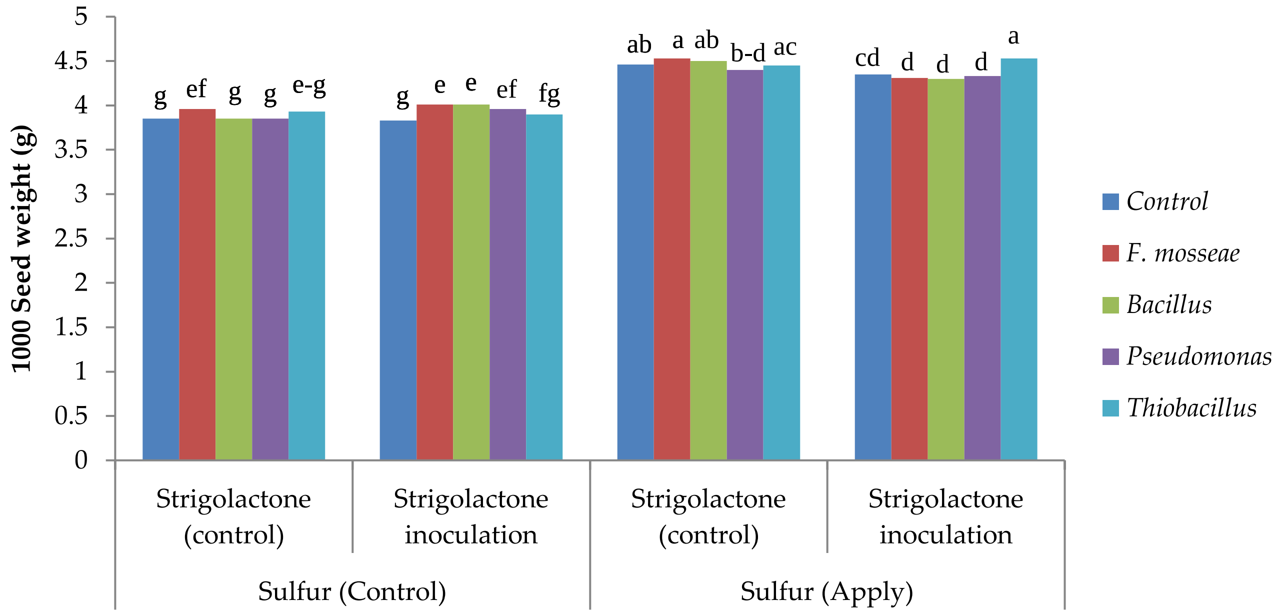

Figure 4. The interaction effect of sulfur spraying and plant growth promoting rhizobacteria inoculation on 1000-seed weight

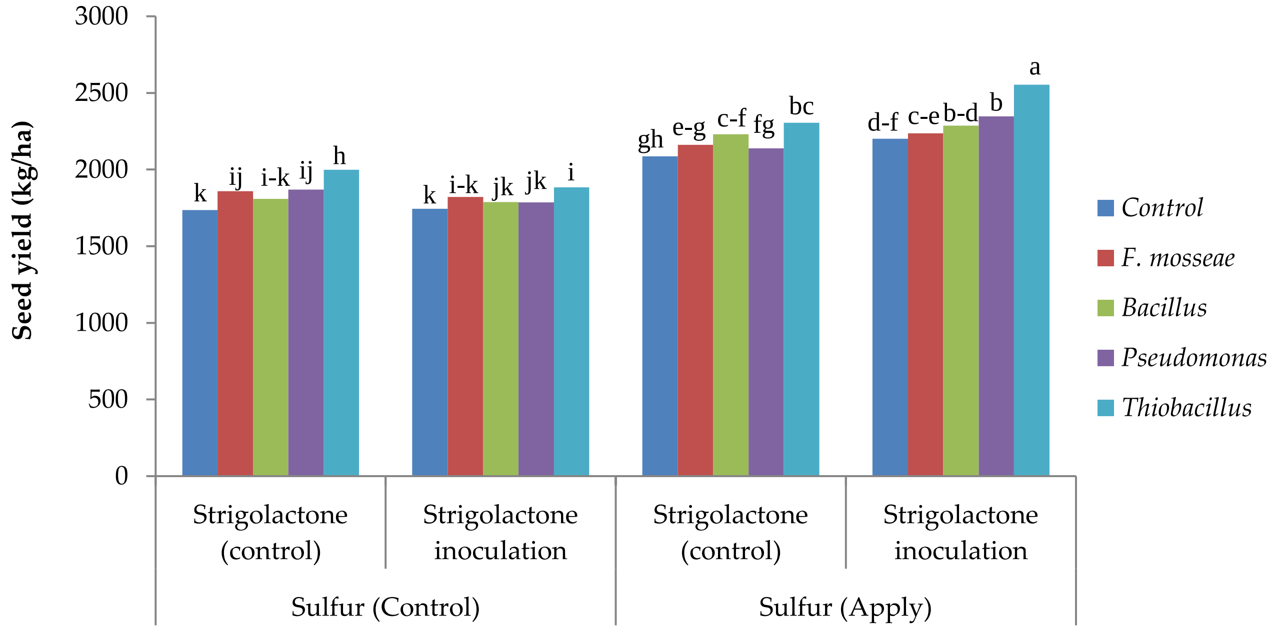

Figure 5. The interaction effect of sulfur spraying and plant growth promoting rhizobacteria inoculation on canola seed yield

The *F. mosseae* significantly enhanced the shoot and root dry matter, plant height, leaf and branch number, photosynthetic efficiency (Mitra et al., 2019). In similar research, the SPAD value increased up to 13% by strigolactone in canola (Ma et al., 2017). They found that strigolactone, improved the growth, leaf chlorophyll, gas exchange characters (net photosynthetic rates, stomatal conductance, concentration of intercellular CO_2, and transpiration rate) and photosystem II quantum yield in oilseed rape.

Considering the increase in the number of pods in the plant under the influence of the treatments in this experiment and based on the negative relationship between the number of pods per plant and the number of seeds per pod, therefore decrease number of seeds per pod seems logical. Ameliorative effect of sulfur on yield attributes such as, pod numbers per plant, seed numbers per pod and 1000-seed weight in canola were found by Ur Rehman et al. (2013) who showed that chlorophyll contents, net assimilation rate, crop growth rate, leaf area index, plant height and number of branches were improved by sulfur. Also, Karaaslan et al. (2020) reported an increasing effect of sulfur on plant height, thousand seed weight, pod per plant, number of primary branches plant and seed per pod and seed yield in canola cultivars. In similar research, sulfur increased the plant height, number of primary branches, pod length and seed attributes such as, number of pods per plant and number of seeds per pod (Poisson et al., 2019). Foliar application of sulfur increased the seed weight of canola by 5.66 and 12.57% (Yari et al., 2022). Also, the numbers of pod per plant increased as 4.33 by sulfur and *Thiobacillus* inoculation (Motamed et al., 2018).

Improving vegetative characters, seed attributes and seed yield of canola varieties by sulfur application were found by Ur Rehman et al. (2013). It seems that in this study, enhanced SPAD number and yield attributes increased seed yield. Yield components were also significantly correlated with canola seed yield (Ma et al., 2015). Enhanced canola seed yield by 7.42% by sulfur related to increasing seed weight (Yari et al., 2022). Rameeh et al. (2019) were found a significant positive correlation between activity of root nitrate reductase and seed yield, they declare that increasing activity of root nitrate reductase in roots by sulfur application, improved the canola seed yield by 17%. Sulfur increased the seed yield via improve of plant height, number of primary branches per plant, number of pods plant, pod length and number of seeds per pod (Tabasi et al., 2017). Also increasing of seed yield and biological yield, in canola proved by sulfur application (Pużyńska et al., 2018; Poisson et al., 2019). In another study, sulfur increased canola yields up to 30% in different places and years (Ma et al., 2015). Sulfur also improved Fe percentage as 15.2% by plant (Baghaie, 2023).

The desirable effects of strigolactones showed on vegetation, biomass and yield under different stress. Exogenous application of strigolactones decrease abscisic acid content whereas enhance auxin and gibberellic acid, after that net photosynthetic rate and the level of carbon dioxide fixation and finally yield increased (Wang et al., 2022). In another study, *Bacillus paralicheniformis* inoculation amplificated the abundance of plants' beneficial microorganisms. In the same ways, *F. mosseae* inoculation intensified uptake and availability of nutrients by plant (Mitra et al., 2019), enhance the root colonization, relative water content, seed yield and yield components (Begum et al., 2019). It has been reported that the significant increase in growth and development, yield components and seed yield under the influence of the use of sulfur and *Thiobacillus* (Motamed et al., 2018).

Asadi Rahmani et al. (2018) attributed the increase in canola yield to enhance uptake of nutrients and also1000- seed weight by Sulfur + *Thiobacillus* inoculation. In similar research, sulfur plus *Thiobacillus* produced the highest number of pods per plant, 1000 grain weight and grain yield of canola (Tabasi et al., 2017). Also, *Pseudomonas fluorescens* enhance activities of antioxidant enzymes hence strengthened the above ground biomass and root length of canola (Kazemi Oskuei et al., 2023).

Neshat et al. (2023) found that inoculated canola by pseudomonas showed higher antioxidant capacity, carotenoids and proline accumulation and total protein under salinity stress. Mohamed & Gomaa (2012) were showed that proline, crude protein contents, IAA and GA3 contents, total free amino acids, and the contents of N, P, K, Ca and Mg enhanced by the inoculation of *Bacillus subtilis* and *Pseudomonas fluorescens*.

CONCLUSION

Canola is one of the valuable oilseed plants that are compatible with large areas with different climatic conditions in Iran. Based on the two-year results of this research, it was observed that the application of treatments increased the seed yield and its components. Among the treatments, sulfur had the greatest effect on increasing the canola seed yield. The effect of strigolactone was positive but minor. Since, based on the research, the usefulness of strigolactone has been reported mostly under stress conditions; it seems that its minor effects were caused by the lack of stress in this experiment. The use of growth-promoting microorganisms was also found to be positive on the studied traits and the most useful in terms of seed yield by *Thiobacillus*.

Compliance with Ethical Standards

Authors' Contributions

SA: Investigation

KM: Methodology, Formal Analysis

BP: Writing – review & editing

AR: Conceptualization, Supervision

All authors read and approved the final manuscript.

Conflict of Interest

The authors declare that there is no conflict of interest.

Ethical Approval

For this type of study, formal consent is not required.

Funding

Not applicable.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

AI Disclosure

The authors confirm that no generative AI was used in writing this manuscript or creating images, tables, or graphics.

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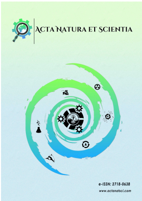

ACTA NATURA ET SCIENTIA

An Exploratory and Future Perspective Review of Adaptogens: A Multifaceted Approach to Enhancing Human Health and Performance

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ABSTRACT

Adaptogens, a class of natural substances derived primarily from plants, have gained significant attention for their potential to enhance human health and performance. These compounds are believed to help the body adapt to stress, improve cognitive function, boost immunomodulation and promote overall well-being. This review article is aimed to discuss the diverse world of adaptogens, exploring their historical use, mechanisms of action and scientific evidence supporting their efficacy. A range of adaptogens will be examined and discussed, including well-known examples like *Withania somnifera* (Ashwagandha), *Rhodiola rosea* and *Panax ginseng*, as well as lesser known but promising candidates. The highlights of the key potential benefits of adaptogens in various health conditions, such as anxiety, depression, fatigue and cognitive decline will be addressed. Additionally, the critical evaluation of the available scientific evidence will be mentioned, highlighting the need for rigorous clinical trials to further validate the claims surrounding adaptogens. By synthesizing information from diverse references, including traditional medicine, modern pharmacology and clinical research, this review aims to provide a comprehensive understanding of adaptogens and their potential applications in promoting human health and performance.

INTRODUCTION

Adaptogens are a class of herbs and plants that have been used in traditional medicine systems for centuries to help the body adapt to various forms of stress. The concept of adaptogens originated in Ayurvedic and Traditional Chinese Medicine (TCM) practices, where certain plants were recognized for their ability to enhance the body's resistance to physical, chemical and biological stressors (Schütz et al., 2006; Panossian & Wikman, 2010). In recent years, there has been a growing interest in adaptogens due to the increasing prevalence of stress-related disorders in modern society and the recognition of their potential health benefits (Simkin & Arnold, 2020). Numerous studies have investigated the effects of adaptogens on the body's response to stress, immune function and overall well-being, suggesting that they may help to maintain homeostasis and support overall health (Nocerino et al., 2000; Panossian & Wikman, 2008). There has been a resurgence of interest in adaptogens in recent years, highlighting the growing recognition of their potential benefits in managing stress-related disorders.

The term "adaptogen" was coined by Soviet scientist N.V. Lazarev in the 1940s to describe substances that help the body adapt to various stressors, both physical and psychological. While there is no universally accepted definition, adaptogens are generally characterized by the following important properties (Lazarev, 1958; Brekhman & Dardymov, 1969; Todorova et al., 2021):

i. Non-specific action: Adaptogens are believed to exert a broad spectrum of effects on the body, rather than targeting specific symptoms or diseases.
ii. Normalization: They help to normalize physiological functions, bringing them back to optimal levels.
iii. Increased resistance to stress: Adaptogens enhance the body's ability to cope with various stressors, including physical, chemical and biological stressors.

Mechanisms of Action

Adaptogens are a class of natural substances that have gained significant attention for their ability to help the body adapt to various stressors (Winston, 2019). These stressors can be physical, such as fatigue and intense exercise, chemical, such as toxins and pollutants or biological, such as infections (Kruk et al., 2019). By enhancing the body's resilience to these stressors, adaptogens can promote overall well-being and improve quality of life (Yance, 2013). The exact mechanisms by which adaptogens exert their effects are complex and not fully understood (Panossian et al., 2018). However, several proposed mechanisms have been identified that work on cellular levels and summarized in Table 1.

Neurotransmitter Modulation

Adaptogens have been found to influence the levels of key neurotransmitters such as dopamine, serotonin, and norepinephrine, which are crucial for regulating mood, cognition and the body's response to stress (Ray et al., 2021). Dopamine is associated with pleasure and reward mechanisms in the brain, affecting motivation and focus (Esch & Stefano, 2004). Serotonin, often referred to as the "feel-good" neurotransmitter, contributes to feelings of well-being and happiness (Dsouza et al., 2020). Norepinephrine is involved in the body's fight-or-flight response, influencing alertness and energy levels (Gruner & Sarris, 2014). By modulating these neurotransmitters, adaptogens can help improve mood, enhance cognitive function and reduce the negative effects of stress (Gulati et al., 2016). This modulation can lead to a more balanced and resilient mental state, making it easier to cope with daily challenges and stressors (Palamarchuk & Vaillancourt, 2021). For example, *Rhodiola rosea*, an adaptogen, has been shown to increase the levels of serotonin and dopamine, thereby improving mood and reducing symptoms of depression and anxiety (Khanum et al., 2005).

Hormonal Regulation

Adaptogens can play a significant role in hormonal regulation, particularly by modulating the Hypothalamic-Pituitary-Adrenal (HPA) axis (Singh et al., 2017). The HPA axis is a central part of the body's stress response system, controlling the production and release of stress hormones such as cortisol (DeMorrow, 2018). Chronic stress can lead to dysregulation of the HPA axis, resulting in elevated cortisol levels and a range of negative health effects, including anxiety, depression and immune suppression (Guilliams & Edwards, 2010). Adaptogens help to normalize the function of the HPA axis, reducing the overproduction of cortisol and promoting a more balanced stress response (Emudainohwo et al., 2023). This hormonal regulation can help mitigate the adverse effects of chronic stress, support mental health and improve overall well-being (Stansbury et al., 2012). For instance, Ashwagandha, a well-known adaptogen, has been shown to lower cortisol levels, thereby reducing stress and anxiety (Gomes, 2023).

Table 1. Summary of potential main mechanism of actions for selected adaptogens

Mechanism*	**Example Adaptogen**	**Effect**
HPA Axis Modulation	Ashwagandha (*Withania somnifera*)	Decreased cortisol levels
Neurotransmitter Regulation	Rhodiola (*Rhodiola rosea*)	Increased serotonin and dopamine levels
Antioxidant Pathways	Schisandra (*Schisandra chinensis*)	Reduction of oxidative stress
Immune Modulation	Ginseng (*Panax ginseng*)	Increased natural killer (NK) cell activity

Note: *Key potential pathways of adaptogen action.

Antioxidant and Anti-Inflammatory Effects

Many adaptogens possess potent antioxidant and anti-inflammatory properties, which are crucial for protecting cells from damage caused by oxidative stress and inflammation (Wróbel-Biedrawa & Podolak, 2024). Oxidative stress occurs when there is an imbalance between free radicals and antioxidants in the body, leading to cellular damage and contributing to aging and various diseases (Sadiq, 2023). Inflammation is a natural response to injury or infection, but chronic inflammation can lead to numerous health issues, including cardiovascular disease, diabetes and autoimmune disorders (Bennett et al., 2018). Adaptogens help to neutralize free radicals, reduce oxidative stress and prevent cellular damage (Panossian, 2017). Their anti-inflammatory effects help to reduce chronic inflammation, promoting healing and preventing disease (Pawar & Shivakumar, 2012; Wróbel-Biedrawa & Podolak, 2024). By providing these protective benefits, adaptogens support overall health and longevity, enhancing the body's resilience to environmental stressors and improving quality of life (Panossian et al., 2021). For example, *Schisandra chinensis*, an adaptogen, has been shown to have strong antioxidant properties, protecting the liver from damage and reducing inflammation (Nowak et al., 2019).

Immune system modulation: Adaptogens may enhance immune function by modulating the activity of immune cells and cytokines (Ratan et al., 2021). This modulation can help the body fight off infections and recover more quickly from illness (Isokauppila & Broida, 2024). Adaptogens support the immunomodulation by increasing the production and activity of white blood cells, which are crucial for defending against pathogens (Panossian & Brendler, 2020). They also help regulate the production of cytokines, which are signaling molecules that mediate and regulate immunity and inflammation (Kaur et al., 2017). By supporting the body's natural defense mechanisms, adaptogens contribute to overall well-being and a healthier lifestyle (Provino, 2010). For instance, *Eleutherococcus senticosus* (Siberian ginseng) has been shown to enhance immune function by increasing the activity of natural killer cells, which play a key role in the body's defense against infections and cancer (Murray, 2020a). This immune-boosting effect helps the body maintain homeostasis and resilience in the face of various stressors.

Overview of Major Adaptogens

The increasing interest in adaptogens is evident in the rising number of scientific studies and consumer demand for adaptogen-containing products (Sama et al., 2022). These adaptogens offer a range of health benefits and can be used to support overall well-being, enhance resilience to stress and improve physical and mental performance (Tóth-Mészáros et al., 2023). This section will provide a brief overview of some of the most well-studied and widely used adaptogens, including:

Ashwagandha (Withania somnifera)

Ashwagandha, scientifically known as *Withania somnifera*, is a perennial shrub native to India, North Africa and the Middle East. It has been extensively used in Ayurvedic medicine for centuries, revered for its rejuvenating and adaptogenic properties (Kumar et al., 2013a, 2023).

Historical use in Ayurvedic medicine

In Ayurvedic medicine, Ashwagandha is considered a Rasayana, a class of herbs believed to promote longevity, vitality and overall well-being (Durg et al., 2015). It has been traditionally used to address a wide range of health issues, including stress, anxiety, insomnia and inflammation (Zahiruddin et al., 2020).

Potential benefits for stress, anxiety and cognitive function

Modern research has begun to validate the traditional uses of Ashwagandha (Joshi & Joshi, 2021). Numerous studies have explored its potential benefits for stress, anxiety and cognitive function (Speers et al., 2021; Arumugam et al., 2024; Lopresti et al., 2019; Akhgarjand et al., 2022; Guo & Rezaei, 2024). It is believed to modulate the HPA axis, a key regulatory system involved in stress response (Sobota et al., 2024). By reducing the levels of cortisol, the primary stress hormone, Ashwagandha may help alleviate symptoms of stress and anxiety (Majeed et al., 2023). Additionally, it has been shown to enhance cognitive function, including memory, attention and reaction time (Xing et al., 2022).

Mechanisms of action, including modulation of the HPA axis and neurotransmitter systems

The mechanisms of action of Ashwagandha are complex and multifaceted. Key mechanisms include (Singh et al., 2011; Chandrasekhar et al., 2012; Pratte et al., 2014; Guo & Rezaei, 2024; Wiciński et al., 2024): HPA Axis Modulation: Ashwagandha can help normalize the HPA axis, reducing excessive cortisol production and promoting a balanced stress response. It may influence the levels of neurotransmitters such as γ-aminobutyric acid (GABA), serotonin and dopamine, which are involved in mood regulation, sleep and cognitive function. Ashwagandha possesses potent antioxidant and anti-inflammatory properties, which can help protect cells from oxidative damage and reduce inflammation.

Clinical evidence supporting its efficacy

Several clinical trials have investigated the efficacy of Ashwagandha in various health conditions. Studies have shown that Ashwagandha can effectively reduce stress, anxiety and symptoms of depression (Lopresti & Smith, 2021). It has also been found to improve cognitive function, particularly in individuals with mild cognitive impairment (Ng et al., 2020). Additionally, Ashwagandha may have potential benefits for physical performance, immune function and reproductive health (Długołęcka et al., 2023). Several clinical trials have provided robust evidence supporting the efficacy of Ashwagandha in various health conditions. A randomized, double-blind, placebo-controlled study by Chandrasekhar et al. (2012) demonstrated that high-concentration full-spectrum Ashwagandha root extract significantly reduced stress and anxiety levels in adults. Participants taking Ashwagandha showed a 44% reduction in stress scores compared to a 5.5% reduction in the placebo group.

A study by Choudhary et al. (2017) investigated the effects of Ashwagandha on cognitive function in adults with mild cognitive impairment. The results indicated significant improvements in memory, executive function, attention and information processing speed in the Ashwagandha group compared to the placebo group (Choudhary et al., 2017). Wankhede et al. (2015) conducted a randomized, double-blind, placebo-controlled trial to assess the impact of Ashwagandha on cardiorespiratory endurance and physical performance in healthy athletic adults. The study found that Ashwagandha supplementation significantly improved VO_2 max (maximum oxygen consumption volume by body during exercise) and overall physical performance.

A study by Davis & Kuttan (2000) explored the immunomodulatory effects of Ashwagandha. The findings revealed that Ashwagandha enhanced the proliferation of lymphocytes and increased the activity of natural killer cells, suggesting a boost in immune function. A clinical trial by Ahmad et al. (2010) examined the effects of Ashwagandha on male fertility. The study reported significant improvements in sperm count, motility and overall semen quality in men treated with Ashwagandha, indicating its potential benefits for reproductive health. These studies collectively highlight the diverse therapeutic potential of Ashwagandha, making it a valuable addition to integrative health practices.

Rhodiola rosea

R. rosea is a popular adaptogen used in traditional medicine to reduce stress, improve mood and enhance cognitive function. It is often found in cold regions, such as the Arctic and mountainous areas (Anghelescu et al., 2018; Brinckmann et al., 2021).

Traditional use in Scandinavian and Russian folk medicine

R. rosea, also known as “golden root” or “arctic root,” has a long history of use in Scandinavian and Russian folk medicine. It was traditionally used to enhance physical endurance, work productivity, longevity and resistance to high altitude sickness. In Siberia, it was given to couples before marriage to enhance fertility and ensure the birth of healthy children. The Vikings reportedly used it to boost their strength and stamina (Panossian et al., 2010; Elise, 2020).

Potential benefits for fatigue, stress and cognitive performance

R. rosea is renowned for its adaptogenic properties, which help the body resist physical, chemical and environmental stress. It has been shown to reduce fatigue, alleviate stress and improve cognitive function. Studies have indicated that Rhodiola can enhance mental performance, particularly under stressful conditions and may also help with symptoms of burnout and mild to moderate depression (Van De Walle & Lamoreux, 2024; Anonymous, 2024a).

Mechanisms of action, including antioxidant and anti-inflammatory effects

The beneficial effects of *R. rosea* are attributed to its active compounds, such as rosavins and salidroside. These compounds exhibit antioxidant properties, protecting cells from oxidative damage. Rhodiola also modulates the stress-response system, reducing cortisol levels and enhancing the production of neurotransmitters like serotonin and dopamine. Additionally, it has anti-inflammatory effects, which contribute to its overall health benefits (Li et al., 2017a; Bernatoniene et al., 2023).

Clinical evidence supporting its efficacy

Clinical studies have demonstrated the efficacy of *R. rosea* in reducing symptoms of stress, fatigue and depression (Panossian & Wikman, 2014; Ivanova Stojcheva & Quintela, 2022). A randomized controlled trial (RCT) conducted by Darbinyan et al. (2000) evaluated the effects of *R. rosea* on stress-induced fatigue in physicians during night shifts. The study found that Rhodiola significantly improved mental performance and reduced fatigue compared to placebo (Darbinyan et al., 2000). Participants reported enhanced cognitive function and reduced symptoms of burnout, indicating Rhodiola’s potential as an adaptogen for stress management. Another RCT by Shevtsov et al. (2003) investigated the impact of Rhodiola on mental fatigue in young, healthy cadets. The study demonstrated that a single dose of Rhodiola extract improved capacity for mental work against a background of fatigue and stress. This suggests that Rhodiola can enhance cognitive function and mental clarity under stressful conditions.

A systematic review by Ishaque et al. (2012) assessed the efficacy of Rhodiola in improving physical and mental fatigue. The review included multiple RCTs and controlled clinical trials, concluding that Rhodiola supplementation could enhance physical performance and reduce fatigue in both healthy individuals and clinical populations. The adaptogenic properties of Rhodiola were highlighted as beneficial for improving endurance and overall physical capacity. A study by Cropley et al. (2015) explored the effects of Rhodiola on symptoms of depression and anxiety. The results indicated that Rhodiola significantly reduced depressive symptoms and anxiety levels in participants, supporting its use as a complementary treatment for mood disorders. The study emphasized Rhodiola’s role in modulating neurotransmitter levels, which may contribute to its antidepressant effects.

A multicenter study by Spasov et al. (2000) examined the effects of Rhodiola on stress symptoms in a diverse population. The study reported significant improvements in stress-related symptoms, including fatigue, irritability and cognitive impairment. Participants experienced enhanced well-being and reduced stress levels, further validating Rhodiola's adaptogenic properties. These studies collectively provide robust evidence for the efficacy of *R. rosea* in managing stress, fatigue, and depression. The adaptogenic effects of Rhodiola make it a valuable addition to integrative health practices, particularly for individuals experiencing high levels of stress and mental fatigue.

Ginseng (Panax ginseng and Eleutherococcus senticosus)

Panax ginseng is a highly valued medicinal herb in traditional Chinese and Korean medicine. It is often used to improve cognitive function, boost energy levels and enhance overall well-being (Coleman et al., 2003). Siberian ginseng is another popular adaptogen used in TCM (Liao et al., 2018). It is often used to boost energy levels, improve mental clarity and enhance immune function.

Diverse species with distinct properties

P. ginseng (Asian ginseng) and *Eleutherococcus senticosus* (Siberian ginseng) are two distinct species with unique properties. *P. ginseng* is known for its potent adaptogenic effects, enhancing physical and mental performance and supporting overall vitality. *Eleutherococcus senticosus*, although not a true ginseng, shares similar adaptogenic properties but is considered milder and more suitable for younger individuals (Huizen & French, 2017; Powers, 2022).

Potential benefits for cognitive function, immune function and energy levels

Both *P. ginseng* and *Eleutherococcus senticosus* are used to boost cognitive function, enhance immune response and increase energy levels (Huizen & French, 2017). *P. ginseng* has been shown to improve memory, concentration and overall mental performance (Gaffney et al., 2001). It also supports immune function by enhancing the activity of natural killer cells (Choi et al., 2017). *Eleutherococcus senticosus* is known for its ability to reduce fatigue, improve physical endurance and support immune health (Gerontakos et al., 2021).

Mechanisms of action, including modulation of neurotransmitter systems and antioxidant effects

The active compounds in *P. ginseng*, known as ginsenosides and the eleutherosides in *Eleutherococcus senticosus*, contribute to their health benefits (Arouca & Grassi-Kassisse, 2013). These compounds modulate neurotransmitter systems, enhancing the release of dopamine and serotonin, which improve mood and cognitive function. They also exhibit antioxidant properties, protecting cells from oxidative stress and reducing inflammation (Smith et al., 2014; Anonymous, 2025).

Clinical evidence supporting its efficacy

Clinical trials have shown that *P. ginseng* can improve cognitive function, reduce fatigue and enhance physical performance. For example, a study found that *P. ginseng* improved cognitive performance in healthy volunteers. Similarly, *Eleutherococcus senticosus* has been shown to enhance physical endurance and reduce the severity of colds and flu (Kennedy et al., 2004; Bleakney, 2008; Ernst, 2010; Bach et al., 2016). These findings support the use of both herbs as effective adaptogens.

Schisandra chinensis

The plant that is called *Schisandra chinensis*, also known as Chinese magnolia vine or five-flavor berry (Sun et al., 2021; Park et al., 2021).

Traditional use in Chinese medicine

Schisandra chinensis, known as "Wu Wei Zi" in Chinese medicine, has been used for centuries to enhance vitality, improve mental clarity and increase physical endurance (Jafernik et al., 2021). It is considered one of the 50 fundamental herbs in TCM and is used to balance the body's energies, support liver function and improve respiratory health (Thompson, 2014; Wu Wei Zi, 2025).

Potential benefits for liver health, respiratory function and cognitive performance

Schisandra is known for its hepatoprotective properties, making it beneficial for liver health. It helps detoxify the liver and protect it from damage. Additionally, Schisandra supports respiratory function by improving lung capacity and reducing cough. It also enhances cognitive performance by improving concentration, memory and mental clarity (Whelan, 2018; Kung, 2019; Levy, 2023).

Mechanisms of action, including antioxidant and anti-inflammatory effects

The active compounds in Schisandra, such as schisandrin, exhibit strong antioxidant and anti-inflammatory properties. These compounds protect the liver from oxidative stress, enhance detoxification processes and reduce inflammation. Schisandra also modulates neurotransmitter levels, which can improve mood and cognitive function (Zhang et al., 2018; Kopustinskiene & Bernatoniene, 2021).

Clinical evidence supporting its efficacy

Clinical studies have shown that Schisandra can improve liver function, enhance cognitive performance and support respiratory health (Wang et al., 2024). For instance, research has demonstrated that Schisandra extract can protect the liver from damage caused by toxins and improve symptoms of chronic hepatitis (Addissouky et al., 2024). Other studies have indicated its potential to enhance mental performance and reduce stress (Yan et al., 2017; Jurcău et al., 2019).

Other notable adaptogens

Apart from Moringa (Masiysa) - which is fast-growing tree is native to areas around the Himalayas, but its cultivation has spread throughout the world, including regions in Egypt – there are other more powerful adaptogens (Alshoaibi, 2021). Moringa leaves are a good source of vitamins and minerals and are sometimes considered an adaptogen due to potential health benefits (Van Wyk, 2019; Meireles et al., 2020). Some of the other common adaptogens could be summarized non-exclusively herein.

Licorice root (Glycyrrhiza glabra)

Licorice root is known for its anti-inflammatory and immune-boosting properties (Darvishi et al., 2022). *Glycyrrhiza glabra* possesses potent antiviral and anti-inflammatory properties, making it a valuable tool in managing respiratory conditions like the common cold, flu, and bronchitis. It effectively soothes irritated mucous membranes in the throat and lungs, alleviating symptoms such as coughing (Otieno, 2019). Licorice root is available in various forms, including teas, tinctures and supplements. However, it's important to exercise caution, as extended use of licorice root can elevate blood pressure and disrupt electrolyte balance, particularly for individuals with hypertension (Otieno, 2019). It is used to soothe gastrointestinal issues, reduce inflammation and support adrenal function (Murray, 2020b). Licorice roots also have antiviral properties, making it useful in treating respiratory infections (Zhang et al., 2021a).

Holy basil (Ocimum sanctum)

Holy basil, also known as Tulsi, is revered in Ayurvedic medicine for its adaptogenic properties (Kumar et al., 2013b). It helps the body cope with stress, supports immune function and improves mental clarity (Thakur & Thapa, 2024). Holy basil also has anti-inflammatory and antioxidant effects, which contribute to its overall health benefits (Yadav et al., 2024).

Astragalus membranaceus

Astragalus is a key herb in TCM, known for its immune-boosting and anti-aging properties (Alipour & Farokhimanesh, 2024). It enhances the body's resistance to stress, supports cardiovascular health and improves energy levels (Shahrajabian et al., 2019). Astragalus is also used to support kidney function and improve overall vitality (Lui et al., 2015).

Cordyceps militaris

Cordyceps is a medicinal mushroom known for its energy-boosting and immune-enhancing properties (Kumar & Kushwaha, 2023). It improves physical performance, supports respiratory health and enhances stamina (Thongsawang et al., 2021). Cordyceps also has antioxidant and anti-inflammatory effects, which contribute to its adaptogenic benefits (Shashidhar et al., 2013). While it's often referred to as a "mushroom," it's more accurately classified as a fungus (Holliday, 2017). *Cordyceps militaris* is a parasitic fungus that grows on insects, particularly caterpillars (Shrestha et al., 2012). It showcases the distinctive orange, club-shaped fruiting bodies that emerge from the infected insect host (Wellham, 2021). *Cordyceps militaris* has gained popularity in recent years due to its potential health benefits, including improved athletic performance, enhanced immune function and anti-aging properties (Abdullah & Kumar, 2023).

Reishi mushroom (Ganoderma lucidum)

Reishi mushroom is a powerful adaptogen used to enhance immune function, reduce stress and improve sleep (Petitto, 2020). It has anti-inflammatory and antioxidant properties, which support overall health and longevity (Luo et al., 2024). Reishi is also known for its ability to improve mental clarity and promote relaxation (Ahmad et al., 2021). It's a type of fungus, not a plant (Mizuno et al., 1995). The characteristic features of Reishi mushrooms, including their distinctive shelf-like shape, red-brown color and white underside (Subramaniam, 2013). Reishi mushrooms are highly valued in TCM for their potential health benefits, such as boosting immunomodulation, reducing stress and improving sleep quality (Zeng et al., 2019).

Adaptogens and Health Conditions

It would be expected from the previously proposed mechanisms by which adaptogens exert their effects some benefits in various health conditions, including the following in this section and Table 2 provides a detailed overview of various adaptogens, their chemical structures, the parts of the organism they are derived from and their medicinal uses. Adaptogens are known for their ability to modulate the body's stress response. They help reduce the secretion of stress hormones like cortisol, which can lower overall stress levels (Panossian & Wikman, 2009). By balancing neurotransmitter levels, adaptogens such as Ashwagandha and *R. rosea* improve mood and emotional well-being (Wal et al., 2019). These herbs enhance resilience to stress by supporting the HPA axis, which regulates the body's response to stress (Lopresti et al., 2022). Adaptogens can significantly enhance cognitive function (Dimpfel et al., 2020). Herbs like *P. ginseng* and *R. rosea* have been shown to improve memory, attention and focus (Joshi Pranav, 2013). They enhance cognitive performance, especially under stressful conditions, by modulating neurotransmitter activity and promoting neurogenesis (Tabassum et al., 2012). Additionally, adaptogens possess neuroprotective effects, protecting brain cells from oxidative stress and inflammation, which can help prevent cognitive decline (Panossian et al., 2019).

Adaptogens play a crucial role in boosting immune function (Sharma et al., 2021). They increase the activity of immune cells such as natural killer cells and macrophages, enhancing the body's resistance to infections (Brindha, 2016). Adaptogens like Astragalus and Reishi mushroom also reduce inflammation by modulating cytokine production and supporting the immune-neuro-endocrine system (Pasdaran et al., 2023). This helps maintain a balanced immune response and prevents chronic inflammation (Tewari et al., 2011). Adaptogens are effective in combating fatigue and boosting energy levels (Ayales, 2019). Herbs like *P. ginseng* and cordyceps improve physical performance and endurance by enhancing mitochondrial function and increasing ATP production (Choi et al., 2020). They help reduce fatigue and exhaustion by supporting adrenal function and HPA axis regulation (Kariatsumari, 2019). This leads to increased vitality and sustained energy throughout the day (Yu et al., 2023). Adaptogens offer a range of additional health benefits. For cardiovascular health, adaptogens like hawthorn and *R. rosea* help regulate blood pressure and improve heart function (Kshirsagara et al., 2023). For liver health, herbs such as schisandra and milk thistle support detoxification and protect against liver damage (Rudzinska & Bogacz, 2012). Adaptogens like maca and *Tribulus terrestris* enhance sexual function by balancing hormones and improving libido (Oyedokun et al., 2024). Additionally, adaptogens have anti-aging properties, reducing oxidative stress and inflammation, which can slow down the aging process (Panossian & Gerbarg, 2016).

Table 2. Summary of adaptogen compounds and their medicinal uses

Adaptogen*	Active Principle/Class	Typical Daily Dosage	Part Used	Organism	Medicinal Uses
Ashwagandha	Withanolides (steroidal lactones)	300–600 mg (root extract, 5% withanolides)	Root	*Withania somnifera*	Reduces stress, anxiety, improves cognitive function, enhances physical performance
Ginseng	Ginsenosides (triterpene saponins)	200–400 mg (root extract)	Root	*Panax ginseng*	Boosts immune function, reduces fatigue, improves cognitive function, anti-inflammatory
Rhodiola	Rosavins, salidroside (phenylpropanoids)	200–600 mg (root extract, 3% rosavins)	Root	*Rhodiola rosea*	Reduces fatigue, enhances mental performance, improves mood, increases physical endurance
Eleuthero	Eleutherosides (saponins)	300–400 mg (root/stem bark extract)	Root, stem bark	*Eleutherococcus senticosus*	Enhances physical performance, reduces stress, boosts immune function
Schisandra	Schisandrins (lignans)	500–1500 mg (berry extract)	Berries	*Schisandra chinensis*	Improves concentration, coordination, endurance, liver protection
Holy Basil	Eugenol, ursolic acid (phenylpropanoids, triterpenoids)	500–1000 mg (leaf extract)	Whole herb	*Ocimum sanctum*	Reduces anxiety, improves focus, boosts immune function
Licorice Root	Glycyrrhizin (triterpene saponin)	200–800 mg (root extract)*	Root	*Glycyrrhiza glabra*	Anti-inflammatory, immune modulation, supports adrenal function
Maca	Macamides, macamides (alkaloids)	1500–3000 mg (root powder)	Root	*Lepidium meyenii*	Enhances libido, improves mood, boosts energy and endurance
Astragalus	Astragalosides (triterpene saponins)	500–1000 mg (root extract)	Root	*Astragalus membranaceus*	Immune boosting, anti-inflammatory, supports cardiovascular health
Cordyceps	Cordycepin (nucleoside analog)	1000–3000 mg (mushroom extract)	Mushroom	*Cordyceps sinensis*	Enhances physical performance, boosts energy, supports respiratory health

Note: *References for given adaptogens are: Størmer et al. (1993), Panossian et al. (1999), Darbinyan et al. (2000), Gonzales et al. (2002), Block & Mead (2003), Cicero et al. (2004), Reay et al. (2005), Coates et al. (2010), Chandrasekhar et al. (2012), Cohen (2014).

Different natural remedies provide different pharmacological approaches in the treatment. For comparative efficiency purpose, it should be noted for example that Ashwagandha primarily modulates the HPA axis, reducing cortisol levels (Chandrasekhar et al., 2012), while *R. rosea* enhances neurotransmitter activity (serotonin/dopamine) to combat fatigue (Darbinyan et al., 2000). For stress-related cognitive decline, Ashwagandha improves memory consolidation, whereas Rhodiola optimizes acute mental performance under fatigue. Ginseng excels in immune enhancement (Reay et al., 2005), whereas Schisandra offers superior hepatoprotection (Panossian et al., 1999).

Overview of Adaptogens and Structure-Activity Relationships (SAR)

Withanolides (Ashwagandha) are steroidal lactones with a C28 ergostane skeleton, featuring a δ-lactone ring at C-22 and C-26 (Kumar et al., 2024). Ginsenosides (Ginseng) are triterpene saponins with a dammarane skeleton, consisting of a four-ring structure (Chopra et al., 2023). Rosavins (Rhodiola) are cinnamyl glycosides, with a phenylpropanoid backbone (Bi et al., 2022). Eleutherosides (Eleuthero) are a group of compounds including saponins and glycosides (Huang et al., 2022). Schisandrins (Schisandra) are dibenzocyclooctadiene lignans (Kortesoja et al., 2019). Eugenol (Holy Basil) is a phenylpropanoid with a methoxy group and an allyl chain (Bendre et al., 2016). Glycyrrhizin (Licorice Root) is a triterpenoid saponin with a glycoside linkage (Li et al., 2020). Macamides (Maca) are fatty acid amides with a benzylamide structure (Alasmari et al., 2019). Astragalosides (Astragalus) are triterpene glycosides with a cycloartane skeleton (Graziani et al., 2019). Cordycepin (Cordyceps) is a nucleoside analog of adenosine, lacking the 3′ hydroxyl group (Du et al., 2021). These structures represent the core chemical frameworks of the compounds found in these adaptogens.

Adaptogens are natural substances known for their ability to help the body adapt to stress and exert a normalizing effect upon bodily processes (Panossian, 2013). The chemical structures of adaptogens play a crucial role in determining their biological activity. The concept of Structure-Activity Relationship (SAR) is fundamental in medicinal chemistry and pharmacology, as it explores the relationship between a compound's chemical structure and its biological effects (Ferro et al., 2006). Withanolides (Ashwagandha) are steroidal lactones that interact with various biological targets, including the HPA axis, to reduce stress and anxiety (Guehairia & Taleb, 2023). The lactone ring and the steroidal backbone are essential for binding to receptors and exerting their adaptogenic effects (Kumar et al., 2024). Ginsenosides (*P. ginseng*) are triterpene saponins that modulate immune function, reduce fatigue and improve cognitive performance (Kennedy & Scholey, 2003). The dammarane skeleton and sugar moieties are critical for their interaction with cell membranes and receptors (Verstraeten et al., 2020). For instance, ginsenoside Rg1, with fewer sugar moieties, is more effective in enhancing cognitive function, while ginsenoside Rb1, with more sugar moieties, has stronger anti-inflammatory properties (Zarneshan et al., 2022; Fan et al., 2024).

Rosavins (*R. rosea*) are phenylpropanoids that enhance mental performance and reduce fatigue (Hamidpour et al., 2015). The presence of glycoside groups enhances the solubility and bioavailability of rosavins (Aktar et al., 2024). Salidroside, a major active component, has been shown to improve mental performance and reduce fatigue more effectively due to its higher bioavailability compared to other rosavins (Zhang et al., 2021b). Eleutherosides (*Eleutherococcus senticosus*) are saponins that enhance physical performance and boost immune function. The aglycone part of eleutherosides is crucial for their adaptogenic effects (Bernatoniene et al., 2023). Modifications in the sugar moieties can alter the compound's ability to enhance physical performance and immune function (Wang et al., 2023). For example, eleutheroside E has been found to be particularly effective in boosting endurance. Schisandrins (*Schisandra chinensis*) are lignans that improve concentration, coordination, and endurance (Goulet & Dionne, 2005). The unique dibenzocyclooctadiene structure of schisandrins is essential for their antioxidant and hepatoprotective activities (Liu et al., 2023a).

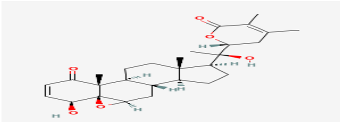
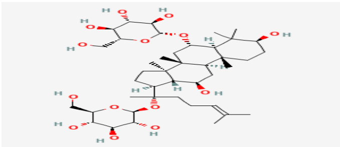
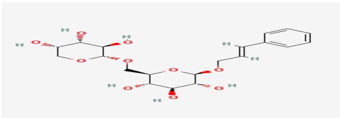
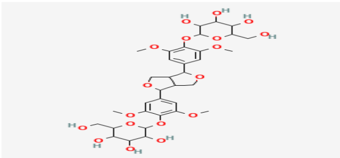
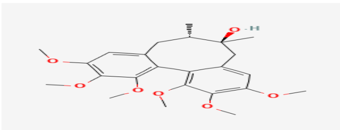
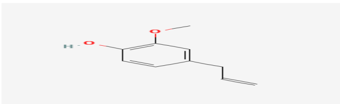
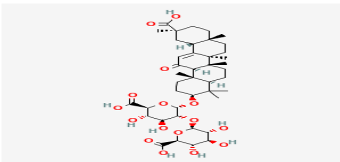
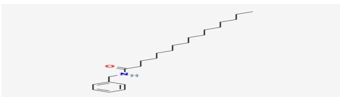
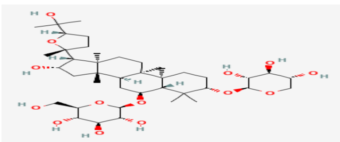
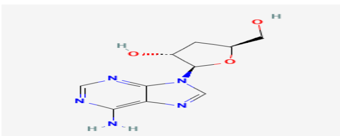
Eugenol (Holy Basil) is a phenylpropanoid with anti-inflammatory and anxiolytic properties. The methoxy group and allyl chain are important for its interaction with enzymes and receptors involved in inflammation and stress response (Saini & Dhiman, 2022). Glycyrrhizin (*Glycyrrhiza glabra*) is a triterpene saponin that modulates immune function and supports adrenal health (Xie et al., 2023). The glycoside linkage and triterpene backbone are critical for its bioactivity and interaction with glucocorticoid receptors (Schwarz et al., 2011). Macamides (*Lepidium meyenii*) are alkaloids that enhance libido and improve mood. The benzylamide structure is essential for their neuroactive properties and interaction with neurotransmitter systems (Pino-Figueroa et al., 2010). Astragalosides (*Astragalus membranaceus*) are triterpene saponins that boost immune function and support cardiovascular health. The cycloartane skeleton and sugar moieties are important for their immunomodulatory effects (Dong et al., 2023). Cordycepin (*Cordyceps sinensis*) is a nucleoside analog that enhances physical performance and supports respiratory health. The absence of the 3′ hydroxyl group in cordycepin is crucial for its ability to inhibit RNA synthesis, which contributes to its anti-cancer and anti-inflammatory properties (Paterson, 2008). Understanding the SAR of these compounds helps in optimizing their therapeutic potential and developing new derivatives with enhanced efficacy and reduced side effects (Singh et al., 2022). These relationships illustrate how specific structural features of adaptogen compounds are directly related to their biological activities, making them valuable additions to integrative health practices.

Table 3 shows simplified examples of adaptogens such as Withanolide D (IUPAC Name[192-201]: (1S,2R,6S,7R,9R,11S,12S,15S,16S)-15-[(1R)-1-[(2R)-4,5-dimethyl-6-oxo-2,3-dihydropyran-2-yl]-1-hydroxyethyl]-6-hydroxy-2,16-dimethyl-8-oxapentacyclo[9.7.0.02,7.07,9.0 12,16]octadec-4-en-3-one), Ginsenoside Rg1 (IUPAC Name: ((2R,3R,4S,5S,6R)-2-[[(3S,5R,6S,8R,9R,10R,12R, 13R,14R,17S)-3,12-dihydroxy-4,4,8,10,14-pentamethyl-17-[(2S)-6-methyl-2-[(2S,3R,4S,5S,6R)-3,4,5-trihydroxy-6-(hydroxymethyl)oxan-2-yl]oxyhept-5-en-2-yl]-2,3,5, 6,7,9,11,12,13,15,16,17-dodecahydro-1H-cyclopenta[a] phenanthren-6-yl]oxy]-6-(hydroxy methyl)oxane-3,4,5-triol), Rosavidin (IUPAC Name: (2R,3R,4S,5S,6R)-2-[(E)-3-phenylprop-2-enoxy]-6[[(2S, 3R,4S,5S)-3,4,5-trihydroxyoxan-2-yl]oxymethyl]oxane -3,4,5-triol), Acanthoside D (IUPAC Name: 2-[4-[6-[3,5-dimethoxy-4-[3,4,5-trihydroxy-6-(hydroxymethyl)oxan-2-yl]oxyphenyl]-1,3,3a,4,6,6a-hexahydrofuro[3,4-c]fura n-3-yl]-2,6-dimethoxyphenoxy]-6-(hydroxymethyl) oxane-3,4,5-triol), Schisandrin (IUPAC Name: (9S,10S)-3,4,5,14,15,16-hexamethoxy-9,10-dimethyltricyclo[10.4.0.02,7]hexadeca-1(16),2,4,6,12, 14-hexaen-9-ol), 4-Allyl-2-methoxyphenol (IUPAC Name: 2-methoxy-4-prop-2-enylphenol), Glycyrrhizic acid (IUPAC Name: (2S,3S,4S,5R,6R)-6-[(2S,3R,4S,5S,6S)-2-[[(3S,4aR,6aR,6bS,8aS,11S,12aR, 14aR,14bS)-11-carboxy-4,4,6a,6b,8a,11,14b-heptamethyl-14-oxo-2,3,4a,5,6,7,8,9,10,12,12a,14a-dodecahydro-1H-picen-3-yl]oxy]-6-carboxy-4,5-dihydroxyoxan-3-yl]oxy-3,4,5-trihydroxyoxane-2-carboxylic acid), Macamide B (IUPAC Name: (N-benzylhexadecanamide), Astragaloside IV (IUPAC Name: (2R,3R,4S,5S,6R)-2-[[(1S,3R,6S,8R,9S,11S,12S,14S,15R,16R)-14-hydroxy-15-[(2R,5S)-5-(2-hydroxypropan-2-yl)-2-methyloxolan-2-yl]-7,7,12,16-tetramethyl-6-[(2S,3R,4 S,5R)-3,4,5-trihydroxyoxan-2-yl]oxy-9-pentacyclo[9.7.0.01,3.03,8.012,16]octadecanyl]oxy]-6-(hydroxymethyl)oxane-3,4,5-triol) and 3′-Deoxyadenosine (IUPAC Name: (2R,3R,5S)-2-(6-aminopurin-9-yl)-5-(hydroxymethyl)oxolan-3-ol).

Overview of Adaptogen Interactions, Contraindications, and Adverse Effects

Adaptogens are widely used for their potential health benefits, but it is crucial to understand their interactions with drugs, contraindications, and possible side effects (Winston, 2019). The following tables provide a detailed overview of these aspects, supported by scientific references in Tables 3-6. Table 4 summarizes the interactions between various adaptogens and drugs, highlighting the potential side effects and adverse reactions (Siwek et al., 2023). Table 5 summarizes the contraindications for various adaptogens, highlighting the conditions and situations where their use should be avoided (Størmer et al., 1993; Panossian et al., 1999; Gonzales et al., 2002; Block & Mead, 2003; Cicero et al., 2004; Reay et al., 2005; Coates et al., 2010; Chandrasekhar et al., 2012; Cohen, 2014; Pratte et al., 2014). Table 6 summarizes the side or adverse effects of various adaptogens and these effects are dose dependent (Størmer et al., 1993; Panossian et al., 1999; Darbinyan et al., 2000; Gonzales et al., 2002; Block & Mead, 2003; Cicero et al., 2004; Reay et al., 2005; Coates et al., 2010; Chandrasekhar et al., 2012; Cohen, 2014).

Table 3. Simplified 2D structures of adaptogens and links to databases for further exploration

Adaptogen	Compound	Chemical Structure (Simplified)	Chemical Formula
Ashwagandha	Withanolides		$C_{28}H_{38}O_6$
Ginseng	Ginsenosides		$C_{42}H_{72}O_{14}$
Rhodiola rosea	Rosavins		$C_{20}H_{28}O_{10}$
Eleuthero	Eleutherosides		$C_{34}H_{46}O_{18}$
Schisandra	Schisandrins		$C_{24}H_{32}O_7$
Holy Basil	Eugenol		$C_{10}H_{12}O_2$
Licorice Root	Glycyrrhizin		$C_{42}H_{62}O_{16}$
Maca	Macamides		$C_{23}H_{39}NO$
Astragalus	Astragalosides		$C_{41}H_{68}O_{14}$
Cordyceps	Cordycepin		$C_{10}H_{13}N_5O_3$

Note: Information for given adaptogens were obtained from National Center for Biotechnology Information (2024a, b, c, d, e, f, g, h, i, j). The structures provided here are simplified representations and may not reflect the full complexity of the molecules. Many of these compounds exist in various forms and isomers, each with its own specific chemical structure.

Table 4. Drug-adaptogen interactions, based on current scientific evidence

Adaptogen*	Drug	Interaction
Withania somnifera	Reboxetine	Testicle pain, ejaculatory dysfunctions
	Sertraline	Severe diarrhea
	Escitalopram	Myalgia, epigastric pain, nausea, vomiting, restless legs syndrome, severe cough
	Paroxetine	Generalized myalgia, ophthalmalgia, ocular hypertension
Eleutherococcus senticosus	Duloxetine	Upper gastrointestinal bleeding
	Paroxetine	Epistaxis
	Sertraline	Vaginal hemorrhage
	Agomelatine	Irritability, agitation, headache, dizziness
Schisandra chinensis	Bupropion	Arthralgia, thrombocytopenia
	Amitriptyline	Delirium
	Fluoxetine	Dysuria
Tribulus terrestris	Citalopram	Generalized pruritus
	Escitalopram	Galactorrhea
	Trazodone	Psoriasis relapse
Coptis chinensis	Mianserin	Arrhythmias
	Mirtazapine	Edema of lower limbs, myalgia
	Fluoxetine	Gynecomastia
Cimicifuga racemosa	Mianserin	Restless legs syndrome
	Paroxetine	Gynecomastia, mastalgia
	Venlafaxine	Hyponatremia
Bacopa monnieri	Agomelatine	Back pain, hyperhidrosis
	Moclobemide	Myocardial infarction
Gynostemma pentaphyllum	Duloxetine	Back pain
Cordyceps sinensis	Sertraline	Upper gastrointestinal bleeding
Lepidium meyenii	Mianserin	Restless legs syndrome
Scutellaria baicalensis	Bupropion	Seizures

Note: * Concluded and extrapolated from Siwek et al. (2023).

That is why it is important for the patients to consult with a healthcare professional before combining adaptogens with medications to ensure safety and efficacy.

Clinical Evidence and Future Directions

The clinical evidence supporting the efficacy and safety of adaptogens is growing, yet it remains limited and often inconsistent (Panossian et al., 2021). Many studies have demonstrated the potential benefits of adaptogens in reducing stress, enhancing cognitive function and boosting immune response (Sánchez et al., 2023). For instance, and as could be extrapolated earlier, clinical trials have shown that *R. rosea* can significantly reduce symptoms of stress-related fatigue and improve mental performance in stressful conditions (Ishaque et al., 2012). Similarly, *P. ginseng* has been found to enhance cognitive function and physical performance (Oliynyk & Oh, 2013). However, these studies often vary in their methodologies, sample sizes and outcome measures, which complicates the interpretation and generalization of the results (Panossian & Wagner, 2005). One of the primary strengths of the existing clinical evidence is the demonstration of adaptogens' ability to modulate the stress response. Adaptogens like ashwagandha and *R. rosea* have been shown to lower cortisol levels, which is a key indicator of stress reduction (Wal et al., 2019). Additionally, adaptogens have been found to improve markers of immune function, such as increased activity of natural killer cells and enhanced resistance to infections (Ramakrishnan et al., 2022). These findings are promising and suggest that adaptogens could play a valuable role in managing stress and supporting overall health.

Table 5. Summary table showing known potential contraindications of various adaptogens, based on current scientific evidence

Adaptogen*	Contraindications
Ashwagandha (*Withania somnifera*)	Pregnancy, hyperthyroidism, autoimmune diseases (e.g., rheumatoid arthritis, lupus)
Ginseng (*Panax ginseng*)	Hypertension, bleeding disorders, insomnia, pregnancy
Rhodiola rosea	Bipolar disorder, pregnancy, breastfeeding
Eleuthero (*Eleutherococcus senticosus*)	Hypertension, sleep disorders, pregnancy, breastfeeding
Schisandra chinensis	Epilepsy, peptic ulcers, pregnancy, breastfeeding
Holy Basil (*Ocimum sanctum*)	Hypoglycemia, anticoagulant therapy, pregnancy, breastfeeding
Licorice Root (*Glycyrrhiza glabra*)	Hypertension, hypokalemia, pregnancy, breastfeeding
Maca (*Lepidium meyenii*)	Hormone-sensitive conditions (e.g., breast cancer, uterine fibroids), pregnancy, breastfeeding
Astragalus (*Astragalus membranaceus*)	Autoimmune diseases, transplant recipients, pregnancy, breastfeeding
Cordyceps (*Cordyceps sinensis*)	Autoimmune diseases, bleeding disorders, pregnancy, breastfeeding

Note: *References for given adaptogens are: Størmer et al. (1993), Panossian et al. (1999), Darbinyan et al. (2000), Gonzales et al. (2002), Block & Mead (2003), Cicero et al. (2004), Reay et al. (2005), Coates et al. (2010), Chandrasekhar et al. (2012), Cohen (2014).

Table 6. Summary showing known dose-dependent side or adverse effects of various adaptogens based on current scientific evidence.

Adaptogen*	Side/Adverse Effects
Ashwagandha (*Withania somnifera*)	Nausea, diarrhea, abdominal pain, drowsiness, headache, allergic reactions
Ginseng (*Panax ginseng*)	Insomnia, headaches, gastrointestinal issues, changes in blood pressure, allergic reactions
Rhodiola rosea	Dry mouth, dizziness, excessive salivation, restlessness, insomnia
Eleuthero (*Eleutherococcus senticosus*)	Drowsiness, headache, gastrointestinal upset, changes in blood pressure
Schisandra chinensis	Gastrointestinal upset, skin rash, allergic reactions
Holy Basil (*Ocimum sanctum*)	Hypoglycemia, nausea, diarrhea, allergic reactions
Licorice Root (*Glycyrrhiza glabra*)	Hypertension, hypokalemia, edema, headache, fatigue
Maca (*Lepidium meyenii*)	Gastrointestinal upset, headache, mood changes
Astragalus (*Astragalus membranaceus*)	Gastrointestinal upset, rash, itching, allergic reactions
Cordyceps (*Cordyceps sinensis*)	Dry mouth, nausea, diarrhea, gastrointestinal upset

Note: *References for given adaptogens are: Størmer et al. (1993), Panossian et al. (1999), Darbinyan et al. (2000), Gonzales et al. (2002), Block & Mead (2003), Cicero et al. (2004), Reay et al. (2005), Coates et al. (2010), Chandrasekhar et al. (2012), Cohen (2014).

Despite these positive findings, there are significant limitations in the current body of research. Many studies on adaptogens are small-scale, short-term and lack rigorous controls. There is also a high degree of variability in the quality and standardization of adaptogen preparations used in these studies. This variability can lead to inconsistent results and makes it difficult to compare findings across different studies (Jarry, 2022). Furthermore, the placebo effect is a notable concern in adaptogen research, as many studies do not adequately control for this factor. Looking forward, there are several challenges and opportunities in conducting high-quality clinical trials on adaptogens. One major challenge is the standardization of adaptogen extracts (Pandey & Tripathi, 2014). Adaptogens are often complex mixtures of bioactive compounds and the concentration of these compounds can vary significantly between different preparations. Standardizing these extracts to ensure consistent potency and composition is crucial for reliable research (Jonas et al., 2023). Additionally, determining the optimal dosage and duration of adaptogen use is essential for understanding their long-term safety and efficacy.

Another important consideration is the selection of appropriate outcome measures. Many studies rely on subjective measures of stress and fatigue, which can be influenced by individual perceptions and biases. Incorporating objective biomarkers, such as cortisol levels and immune cell activity, can provide more reliable and quantifiable data. Moreover, long-term studies are needed to assess the sustained effects of adaptogens and their potential side effects over extended periods. Hence, while the current clinical evidence on adaptogens is promising, more rigorous and standardized research is needed to fully understand their efficacy and safety. Addressing the challenges of standardization, dosage and outcome measures will be critical in advancing the field of adaptogen research (Prinsen et al., 2016; Panossian, 2017; Jarry, 2022; Gerontakos et al., 2020). Future studies should focus on large-scale, long-term clinical trials with well-defined protocols to provide more definitive evidence on the health benefits of adaptogens.

Adaptogens and Personalized Medicine

Personalized medicine, also known as precision medicine, is an innovative approach that tailors medical treatment to the individual characteristics of each patient. This approach considers genetic, environmental and lifestyle factors to provide more effective and targeted therapies (MedlinePlus, 2024). Adaptogens, with their diverse range of bioactive compounds, fit well into the personalized medicine paradigm (Vicente et al., 2020). By understanding an individual's specific stressors and physiological responses, healthcare providers can select the most appropriate adaptogens to support their health.

Genetics play a crucial role in how individuals respond to adaptogens. Genetic variations can influence the metabolism, efficacy and safety of adaptogens. For instance, polymorphisms in genes encoding for enzymes involved in the metabolism of adaptogens can affect how these compounds are processed in the body (Anonymous, 2024b). Cytochrome P450 enzymes, which are responsible for the metabolism of many drugs and natural compounds, exhibit genetic variability that can lead to differences in adaptogen metabolism (Anonymous, 2024c). Understanding these genetic variations can help in selecting the right adaptogen and dosage for each individual (Hossam Abdelmonem et al., 2024).

Environmental and lifestyle factors also significantly impact the effectiveness of adaptogens (Cybel, 2024). Factors such as diet, stress levels, physical activity and exposure to toxins can influence how the body responds to adaptogens (Anonymous, 2024d). For example, individuals with high levels of chronic stress might benefit from adaptogens like Ashwagandha, which has been shown to modulate the HPA axis and reduce cortisol levels (Plante, 2024). Conversely, those needing cognitive support might find *R. rosea* more beneficial due to its effects on mental performance and fatigue reduction (Ishaque et al., 2012; Turner, 2024). Personalized medicine can also consider potential interactions between adaptogens and other medications, ensuring safe and effective use tailored to the individual's unique health profile.

Biomarkers are measurable indicators of biological processes, and they play a critical role in personalized medicine (Jain, 2021). By identifying specific biomarkers, healthcare providers can tailor adaptogen therapy to the individual's needs (Yance, 2013; Jamal, 2023). For example, cortisol levels can be used as a biomarker to assess stress and determine the effectiveness of adaptogens like Ashwagandha in reducing stress (Haber et al., 2024). Similarly, inflammatory markers such as C-reactive protein (CRP) can help in selecting adaptogens with anti-inflammatory properties, such as ginseng or turmeric (Garcia-Bailo et al., 2011).

Several case studies and clinical trials have demonstrated the benefits of personalized adaptogen therapy (Winston, 2019). For instance, a study on the use of *R. rosea* in individuals with chronic fatigue syndrome showed significant improvements in fatigue levels and overall well-being when the adaptogen was tailored to the individual's specific needs (Ayales, 2019; Elise, 2020). Another study on the use of Ashwagandha in individuals with high stress levels found that personalized dosing based on cortisol levels resulted in better outcomes compared to standard dosing (Quinones et al., 2025).

Integrating adaptogens into personalized medicine involves a comprehensive assessment of the individual's health status, including genetic testing, biomarker analysis and lifestyle evaluation (Panossian & Efferth, 2022). This holistic approach ensures that the selected adaptogens are well-suited to the individual's unique needs (Yance, 2022). Healthcare providers can use tools such as genetic testing kits, wearable devices for monitoring physiological parameters and personalized health apps to gather data and make informed decisions about adaptogen therapy.

While the integration of adaptogens into personalized medicine holds great promise, there are several challenges to consider (Yance, 2013; Jamal, 2023; Balkrishna et al., 2024). One of the main challenges is the variability in the quality and standardization of adaptogenic products (Kurkin & Ryazanova, 2021). Ensuring that adaptogens are sourced from reputable suppliers and standardized for their active compounds is crucial for their effectiveness and safety (Nunez, 2024). Additionally, more research is needed to understand the long-term effects of adaptogen use and their interactions with other medications (Panossian et al., 2021). Future directions in personalized adaptogen therapy include the development of advanced diagnostic tools and technologies for real-time monitoring of biomarkers and physiological responses (Pokushalov et al., 2024). The use of artificial intelligence and machine learning algorithms to analyze data and predict the most effective adaptogen combinations is another exciting area of research (Siddiqui et al., 2025). As our understanding of the human genome and the mechanisms of adaptogens continues to grow, personalized adaptogen therapy will become increasingly precise and effective.

Adaptogens and Nanotechnology

Nanotechnology, the manipulation of matter on an atomic or molecular scale, offers exciting possibilities for enhancing the efficacy and delivery of adaptogens (Teli et al., 2024). By incorporating adaptogens into nanoparticles, researchers can improve their bioavailability, stability and targeted delivery to specific tissues or cells (Stanisz et al., 2024). This approach can maximize the therapeutic benefits of adaptogens while minimizing potential side effects (Milicic et al., 2022).

One of the main challenges with adaptogens is their bioavailability, which refers to the proportion of a substance that enters the bloodstream and has an active effect (Potoroko et al., 2018; Panossian et al., 2021). Many adaptogens have low bioavailability due to poor solubility, instability in the gastrointestinal tract or rapid metabolism (Ayub et al., 2024). Nanotechnology can address these issues by encapsulating adaptogens in nanoparticles, which can protect them from degradation and enhance their absorption (Chatterjee & Khan, 2025). For example, curcumin, the active compound in Turmeric, has low bioavailability due to its poor solubility and rapid metabolism (Abd El-Hack et al., 2021). Researchers have developed curcumin nanoparticles that significantly enhance its bioavailability and therapeutic effects (Kakkar et al., 2011; Abd El-Hack et al., 2021). Similar approaches can be applied to other adaptogens to improve their efficacy (Uddin, 2024).

Nanoparticles can be engineered to target specific tissues or cells, enhancing the therapeutic effects of adaptogens while reducing side effects (Sheik et al., 2021). This targeted delivery is achieved by modifying the surface of nanoparticles with ligands that bind to specific receptors on the target cells244. For instance, nanoparticles can be designed to target cancer cells, delivering adaptogens with anti-cancer properties directly to the tumor site (Abdul Azeez et al., 2018; Anarjan, 2019). A study on the use of nanoparticle-encapsulated Ginseng extract demonstrated enhanced anti-cancer activity and reduced toxicity compared to free Ginseng extract (Jeon et al., 2023). This targeted delivery approach can be applied to other adaptogens to treat various health conditions more effectively.

Nanotechnology can also enable the sustained release of adaptogens, providing a steady and prolonged therapeutic effect. This is particularly beneficial for adaptogens that require consistent levels in the bloodstream to be effective. Sustained release formulations can reduce the frequency of dosing and improve patient compliance. For example, sustained release nanoparticles of Ashwagandha extract have been developed to provide a prolonged anti-stress effect. This approach ensures that the adaptogen remains active in the body for an extended period, enhancing its therapeutic benefits (Manjunath et al., 2023).

Biological barriers, such as the blood-brain barrier (BBB), can limit the effectiveness of adaptogens in treating certain conditions. Nanoparticles can be designed to cross these barriers, delivering adaptogens to otherwise inaccessible sites. This is particularly relevant for adaptogens used in neuroprotection and cognitive enhancement. A study on the use of nanoparticles encapsulated *R. rosea* extract demonstrated its ability to cross the BBB and exert neuroprotective effects in a model of Alzheimer's disease (Shilo et al., 2015; Tang et al., 2017; Liu et al., 2023b). This opens up new possibilities for using adaptogens in the treatment of neurological disorders.

While nanotechnology offers numerous benefits for adaptogen delivery, it is essential to consider the safety and efficacy of nanoparticle formulations (Arifin et al., 2019). The size, shape and surface properties of nanoparticles can influence their interaction with biological systems and their potential toxicity (Albanese et al., 2012). Rigorous testing and evaluation are necessary to ensure that nanoparticle-based adaptogen formulations are safe for human use (Sukhanova et al., 2018).

The integration of nanotechnology with adaptogens represents a promising frontier in both botanical medicine and advanced therapeutic delivery systems (de Jesus Silva et al., 2023). Future research will focus on optimizing nanoparticle formulations, exploring new materials for nanoparticle construction, and conducting clinical trials to evaluate the safety and efficacy of these advanced delivery systems (Liu et al., 2024). Additionally, the development of multifunctional nanoparticles that combine adaptogens with other therapeutic agents or diagnostic tools is an exciting area of research (Pięta et al., 2023). These multifunctional nanoparticles can provide synergistic effects, enhancing the overall therapeutic outcome (Gupta et al., 2022). At the end, the combination of adaptogens and nanotechnology holds great potential for improving the effectiveness and precision of natural therapies. By enhancing bioavailability, enabling targeted delivery, providing sustained release and overcoming biological barriers, nanotechnology can maximize the therapeutic benefits of adaptogens and open up new possibilities for their use in personalized medicine and beyond.

Incorporation of Nanorobotics and Adaptogens in Space Travel: A Scientific Perspective

Space travel presents a unique set of challenges that can significantly impact human health (Eissa, 2018). The harsh environment of space, characterized by microgravity, radiation, isolation and confinement, poses risks to astronauts' physical and mental well-being (Shah et al., 2024). To mitigate these risks, innovative solutions are required. The incorporation of nanorobotics and adaptogens in space travel is a scientifically logical approach that holds great promise for enhancing astronaut health and performance during long-duration missions (Kalia, 2022).

Space travel exposes astronauts to a variety of stressors that can affect their health (Arone et al., 2021). These include:

(i) *Microgravity*: Prolonged exposure to microgravity leads to muscle atrophy, bone density loss and fluid shifts that can affect vision and cardiovascular function (Iwase et al., 2020).

(ii) *Radiation*: Space radiation, including galactic cosmic rays and solar particle events, increases the risk of cancer, central nervous system effects and other health issues (Cucinotta et al., 2014).

(iii) *Isolation and Confinement*: The psychological effects of isolation and confinement can lead to stress, anxiety and depression (Pagel & Choukèr, 2016).

(iv) *Distance from Earth*: The vast distance from Earth complicates medical interventions and emergency responses (Clément, 2011).

(v) *Hostile/Closed Environments*: The closed environment of spacecraft can lead to issues with air quality, microbial contamination and limited resources (Mogul & Moeller, 2022).

Nanorobotics involves the use of nanoscale robots (nanobots) that can perform tasks at the molecular level (Eissa, 2025). These nanobots can be designed for various applications, including drug delivery, diagnostics and repair of biological tissues (Li et al., 2017b). In the context of space travel, nanorobots offer several advantages:

(i) *Targeted Drug Delivery*: Nanobots can deliver adaptogens and other medications directly to specific tissues or cells, enhancing their efficacy and reducing side effects (Wahi et al., 2024).

(ii) *Real-Time Monitoring*: Nanobots equipped with sensors can monitor astronauts' health in real-time, detecting early signs of health issues and providing immediate feedback (Roda et al., 2018).

(iii) *Repair and Maintenance*: Nanobots can repair damaged tissues, close micro-holes in spacecraft and perform maintenance tasks, reducing the need for risky extravehicular activities (EVAs) (Chui & Kissner, 2000).

The integration of adaptogens and nanorobotics in space travel can create a synergistic effect, enhancing the overall health and performance of astronauts (Kalia, 2022). There are several approaches through which this integration can be achieved:

(i) *Enhanced Bioavailability of Adaptogens:* Nanotechnology can improve the bioavailability of adaptogens, ensuring that they are effectively absorbed and utilized by body (Babii et al., 2017). For example, encapsulating adaptogens in nanoparticles can protect them from degradation and enhance their absorption in the gastrointestinal tract (Bandiwadekar et al., 2022).

(ii) *Targeted Delivery of Adaptogens:* Nanobots can deliver adaptogens directly to specific tissues or cells, enhancing their therapeutic effects (Anto et al., 2025). For instance, nanobots can target the brain to deliver adaptogens that improve cognitive function and reduce stress (Kakkar et al., 2016).

(iii) *Sustained Release of Adaptogens:* Nanotechnology can enable the sustained release of adaptogens, providing a steady and prolonged therapeutic effect (Li et al., 2021; NASA, 2020; NASA Spinoff, 2024). This is particularly beneficial for adaptogens that require consistent levels in the bloodstream to be effective (Shimer, 2004; Smart Adaptogen, 2024).

(iv) *Real-Time Health Monitoring:* Nanobots equipped with sensors can monitor astronauts' health in real-time, detecting early signs of stress, fatigue or other health issues (NASA, 2020; NASA Spinoff, 2024). This information can be used to adjust adaptogen therapy as needed, ensuring optimal health and performance (Shimer, 2004; Smart Adaptogen, 2024).

(v) *Repair and Maintenance:* Nanobots can repair damaged tissues and perform maintenance tasks, reducing the need for risky EVAs. This can help maintain the health and safety of astronauts during long-duration missions (Palencia, 2020; Hutson, 2023; White, 2024; Space Voyage Ventures Team, 2024).

Finally, industrialization of these technologies requires stringent and consistent quality that could be achieved using Statistical Process Control (SPC) techniques. SPC methodologies have been used extensively in various fields, including industrial and non-industrial sectors (Eissa, et al, 2022; Eissa, 2023a, 2023b). They provide indispensable means to monitor, adjust, control and improve various inspection characteristics to yield products of high safety, quality and efficacy with reproducible and predictable properties.

CONCLUSION

Adaptogens are promising natural substances that enhance health and performance by modulating neurotransmitter systems, hormonal balance, and immune function. Traditional medicine values them, and modern research supports their benefits. However, consulting healthcare professionals and conducting rigorous clinical trials are essential to establish their efficacy and safety. Standardizing extracts and identifying optimal dosages are critical challenges. Objective biomarkers in trials can validate adaptogens' effects. Future research should explore their synergistic effects with other treatments. Adaptogens fit well into personalized medicine and can be enhanced with nanotechnology for better delivery and efficacy, benefiting both terrestrial and space medicine. Embracing SPC tools for industrialization will be crucial to achieve large and widespread use of this unique technologies in a safe, predictable and consistent inspection properties through appropriate quality tests.

Compliance with Ethical Standards

Conflict of Interest

The author declares that there is no conflict of interest.

Ethical Approval

For this type of study, formal consent is not required.

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Data Availability

Data availability is not applicable to this article as no new data were created or analyzed in this study.

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AI-assisted technology was not used in the preparation of this work, except for grammar and spelling checks as an assistant writing tool & organizer.

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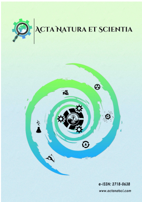

ACTA NATURA ET SCIENTIA
PRENSIP

KBRN Eğitimlerinde Kritik Ekipman Kullanım Hataları ve Operasyonel Risklerin Yönetimi: Entegre Bir Yaklaşım

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Ö Z E T

Bu çalışma, kimyasal, biyolojik, radyolojik ve nükleer (KBRN) eğitimlerinde ortaya çıkan insan hatalarının nedenlerini çok katmanlı bir sistem yaklaşımıyla incelemekte ve bu hataların eğitimsel süreçlere entegrasyonunu sağlayan bütünleşik bir değerlendirme modeli önermektedir. Çalışma aynı zamanda KBRN eğitimlerinde sıkça karşılaşılan ekipman kullanım hatalarının yalnızca teknik eksikliklerden değil, bilişsel yük, ergonomik kısıtlar, çevresel faktörler ve karar verme süreçlerindeki karmaşadan kaynaklandığını ortaya koymaktadır. Bununla birlikte, insan faktörleri kuramlarını, ergonomik analiz yaklaşımlarını ve operasyonel risk yönetimi ilkelerini birleştirerek hataların kök nedenlerini açıklamaya odaklanmıştır. Kuramsal çerçeve çok katmanlı bariyer mantığına dayanan Swiss Cheese modeli, hata sınıflandırma sistematiği sunan HFACS ve insan–ekipman–çevre etkileşimini irdeleyen SHELL modelinin sentezine dayanmaktadır. Bu üç modelin bütüncül olarak uygulanması, KBRN eğitimlerinde güvenlik kültürünün geliştirilmesine, senaryo temelli öğrenme yöntemlerinin etkinliğinin artırılmasına ve kişisel koruyucu ekipman kullanımında ergonomik optimizasyonun sağlanmasına katkı sunmaktadır. Çalışma insan hatası kuramlarını KBRN eğitimleri bağlamına uyarlayan disiplinler arası bir entegrasyon modeli önermesiyle diğer çalışmalardan öne çıkmaktadır. Elde edilen sonuçlar, model temelli eğitim tasarımının karar destek araçları ve standardize edilmiş iş akışlarıyla bütünleştirildiğinde operasyonel güvenliğin ölçülebilir biçimde güçlendiğini göstermektedir.

Critical Equipment Errors and Operational Risk Management in CBRN Training: An Integrated Approach

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ABSTRACT

This study investigates the causes of human error in chemical, biological, radiological, and nuclear (CBRN) training using a multilayered systems approach, and proposes an integrated assessment model that facilitates the integration of these errors into the training processes. The study also reveals that equipment usage errors commonly encountered in CBRN training are not solely due to technical deficiencies, but also arise from cognitive load, ergonomic constraints, environmental factors, and complexities in decision-making processes. Furthermore, it focuses on explaining the root causes of errors by integrating human factors theories, ergonomic analysis approaches, and principles of operational risk management. The theoretical framework is based on the synthesis of the Swiss Cheese model, which relies on the multi-layered barrier concept, the HFACS error classification system, and the SHELL model, which examines human-equipment-environment interactions. The holistic application of these three models contributes to the development of a safety culture in CBRN training, enhances the effectiveness of scenario-based learning methods, and facilitates ergonomic optimization in the use of personal protective equipment. The study stands out from others by proposing an interdisciplinary integration model that adapts human error theories to the context of CBRN training. The results indicate that when model-based training design is integrated with decision support tools and standardized workflows, operational safety is measurably strengthened.

GİRİŞ

Kimyasal, biyolojik, radyolojik ve nükleer (KBRN) tehditler hem doğal hem de insan kaynaklı olayların giderek karmaşıklaştığı günümüzde, güvenlik ve sağlık sistemleri için en yüksek düzeyde hazırlık gerektiren senaryolardır. KBRN olaylarının çok disiplinli yapısı, teknik bilgi birikimi kadar insan faktörleri, karar verme süreçleri ve örgütsel koordinasyonun da eğitim kapsamına dahil edilmesini zorunlu kılmaktadır (Qzih & Ahmad, 2024). Bu nedenle KBRN hazırlık düzeyinin yalnızca ekipman veya protokol temelli değil, aynı zamanda bilişsel, psikolojik ve kurumsal yeterliliklerin bütüncül bir birleşimi olarak ele alınması gerekmektedir (Farhat vd., 2024).

Son yıllarda yapılan araştırmalar, KBRN olaylarına müdahalede en zayıf halkanın çoğunlukla teknik yetersizlik değil, insan kaynaklı hatalar olduğunu göstermektedir. Özellikle kişisel koruyucu donanım (PPE) kullanımı, zaman baskısı altında karar verme, bilişsel yük ve ekip içi iletişim eksiklikleri hata olasılığını artırmaktadır (Giaume vd., 2024; Gkikas vd., 2025). Anderson & Boddington (2024) koruyucu ekipmanın ergonomik sınırlılıklarının klinik performans üzerinde bilişsel yük yarattığını belirtirken; Razak vd. (2023) uygun eğitim ve standardizasyonun bu olumsuz etkileri azaltabileceğini vurgulamıştır. PPE kullanımına ilişkin fizyolojik ve psikolojik etkilerin yanı sıra, çevresel stresörler ve ekipman tasarımı arasındaki dengesizliklerin de hata riskini artırdığı görülmektedir (Son, 2023; Lucena vd., 2026).

Eğitim sistemleri açısından bakıldığında, mevcut KBRN müfredatlarının büyük bölümü bilgi aktarımına dayalı olup senaryo temelli uygulamalarda ise sınırlı kalmaktadır. Oysa güncel literatür, etkili KBRN eğitimlerinin bilişsel yük yönetimi, stres toleransı, ergonomi ve örgütsel öğrenme unsurlarını birlikte ele alması gerektiğini göstermektedir (Razak vd., 2023; Farhat vd., 2024). Bu çerçevede, Bogdan-Ioan vd. (2024) ve Rimpler-Schmid vd. (2021) Avrupa'daki KBRN hazırlık politikalarının hala operasyonel standartlarla entegre bir eğitim paradigmasından yoksun olduğunu vurgulamaktadır. Ayrıca Malizia vd. (2025) tarafından önerilen "exposome" tabanlı bütüncül risk değerlendirme yaklaşımı, KBRN tehditlerinin yalnızca çevresel maruziyet açısından değil aynı zamanda bireysel ve kurumsal dayanıklılık düzeyleri açısından da analiz edilmesi gerektiğini öne sürmektedir.

Son dönemde teknolojik yenilikler KBRN eğitimlerinde bilişsel ve davranışsal yetkinliklerin geliştirilmesi için yeni olanaklar sunmaktadır. Sanal gerçeklik (VR) ve karma gerçeklik (XR) uygulamaları, riskli senaryoların güvenli ortamda tekrarını sağlayarak öğrenme sürecini güçlendirmektedir (Regal vd., 2023; Hancko vd., 2025). Benzer biçimde, makine öğrenmesi ve yapay zeka tabanlı karar destek sistemleri, eğitim sırasında risk farkındalığını artırmakta ve müdahale hatalarını önleyebilmektedir (Kegyes vd., 2024; Nemeth vd., 2024). Bu sistemlerin etkin biçimde kullanımı, eğitimin bireysel performans ölçümleriyle ilişkilendirilmesine ve karar süreçlerinin veri temelli olarak optimize edilmesine katkı sağlamaktadır.

İnsan faktörlerinin eğitim ve operasyonel süreçlere sistematik biçimde entegre edilmemesi halinde teknolojik çözümler tek başına kalıcı güvenlik artışı sağlamamaktadır (Nazari vd., 2023). Güncel araştırmalar, özellikle stres altında karar verme, durum farkındalığı, iletişim ve ekip koordinasyonu gibi bilişsel değişkenlerin KBRN görev başarısında belirleyici olduğunu göstermektedir (Giaume vd., 2024; Bearman vd., 2025). Dolayısıyla, KBRN eğitimlerinde insan performansını etkileyen psikolojik ve ergonomik faktörlerin modellenmesi hem bireysel öğrenme çıktılarının hem de kurumsal hazırlık kapasitesinin artırılmasında kritik rol oynamaktadır.

Bu çalışma, literatürdeki teknik odaklı KBRN eğitim yaklaşımlarını aşarak, insan faktörleri, ergonomi ve sistem güvenliği arasındaki ilişkiyi açıklayan bütüncül bir değerlendirme modeli önermektedir. Çalışma aynı zamanda Swiss Cheese, HFACS ve SHELL modellerini KBRN eğitim bağlamında birleştirerek hataları yalnızca bireysel performans sorunları değil sistemsel etkileşimlerin çıktısı olarak ele almaktadır. Böylelikle, eğitimlerin tasarımında risk yönetimi, örgütsel öğrenme ve insan–donanım etkileşimi gibi unsurların ölçülebilir biçimde bütünleştirilmesi hedeflenmektedir. Ayrıca, bu çalışma KBRN eğitimlerinde güvenlik kültürünün güçlendirilmesine ve sürdürülebilir bir hata önleme sistematiğinin geliştirilmesine kuramsal zemin sunmaktadır.

KURAMSAL ÇERÇEVE VE MODEL YAKLAŞIMI

KBRN olayları, doğaları gereği çok disiplinli bilgi, yüksek stres altında karar verme ve karmaşık insan–teknoloji etkileşimlerinin eşzamanlı yönetimini gerektirmektedir. Bu nedenle eğitim süreçlerinin yalnızca prosedür aktarımına değil hataların bilişsel, örgütsel ve çevresel kökenlerini açıklayan kuramsal modellere dayanması zorunludur. Literatürde, insan hatasını anlamak ve önlemek amacıyla geliştirilmiş çeşitli sistem yaklaşımları bulunmakla birlikte, KBRN bağlamına en uygun modeller arasında Swiss Cheese modeli, HFACS (Human Factors Analysis and Classification System) ve SHELL (Software, Hardware, Environment, Liveware and Liveware) modeli öne çıkmaktadır (Reason, 2000; Woodcock, 2013). Bu modellerin bütünleştirilmesi, hataları bireysel yetersizlikten ziyade sistemsel etkileşimlerin sonucu olarak ele alan bütüncül bir değerlendirme çerçevesi sunmaktadır. KBRN eğitimlerinde en sık kullanılan bu üç modelin temel özellikleri, avantajları ve sınırlılıkları Tablo 1'de özetlenerek karşılaştırılmıştır.

Swiss Cheese modeli sistemsel bariyerlerdeki zafiyetlerin hata zincirine dönüşümünü açıklarken (Reason, 2000); HFACS modeli insan hatalarını kurumsal, operasyonel ve bireysel düzeyde çok katmanlı biçimde analiz etmektedir (Woodcock, 2013; Razak vd., 2023). SHELL modeli ise insan–donanım–çevre etkileşimini merkeze alarak ergonomik dengesizlikleri değerlendirmektedir (Anderson & Boddington, 2024). Üç model birlikte ele alındığında, KBRN eğitimlerinin yalnızca teknik yeterlik değil, aynı zamanda sistemsel dayanıklılık ve bilişsel farkındalık temelleri üzerine kurulması gerektiği dikkat çekmektedir.

Table 1. Comparison of human factors models used in CBRN training
Tablo 1. *KBRN eğitimlerinde kullanılan insan faktörü modellerinin karşılaştırması*

Model	Odak Noktası	Avantaj	Sınırlılık	Temel Kaynak(lar)
Swiss Cheese	Sistem hataları ve bariyer zafiyetleri	Sistemsel analiz sağlaması	İnsan faktörünü dolaylı ele alması	Reason (2000)
HFACS	İnsan hatalarının çok katmanlı nedenleri	Kurumsal–bireysel hata ilişkisini açıklaması	Veri gereksinimin yüksek olması	Woodcock (2013), Razak vd. (2023)
SHELL	İnsan–donanım–çevre etkileşimi	Ergonomik analiz ve farkındalık sağlaması	Sübjektif değerlendirme riski	Anderson & Boddington (2024)

Swiss Cheese Modeli

Reason (2000) tarafından geliştirilen Swiss Cheese modeli (çok katmanlı bariyer mantığı), güvenlik sistemlerinde birbiri ardına dizilmiş savunma katmanlarının her birinde potansiyel zafiyetlerin bulunabileceği varsayımına dayanmaktadır. Bu katmanlardaki "deliklerin" zaman içinde hizalanması, hataların zincirleme biçimde ilerlemesine neden olmaktadır (Reason, 2000). Modelin KBRN eğitimleri bağlamına uyarlanması, hata oluşumunun yalnızca bireysel düzeyde değil, eğitim müfredatı, ekipman kullanımı, çevresel stresörler ve organizasyonel yönetim gibi çoklu düzlemlerde gerçekleştiğini göstermektedir.

Kişisel koruyucu ekipman (PPE) kullanımı sırasında yaşanan hatalar, ekipman ergonomisi, yetersiz uygulamalı eğitim ve yüksek bilişsel yükün bir araya gelmesiyle ortaya çıkabilir. Anderson & Boddington (2024) PPE'nin klinik ve operasyonel performans üzerindeki bilişsel yükü artırdığını, bunun da hata oranlarını yükseltebildiğini belirtmiştir. Benzer biçimde, Lucena vd. (2026) saha koşullarında koruyucu giysi kullanımının fiziksel performansı sınırladığını ancak uygun eğitim ve standardizasyonla bu etkinin azaltılabileceğini göstermiştir.

Bu bağlamda Swiss Cheese modeli, eğitim programlarının yalnızca içerik değil süreç güvenliği odaklı biçimde yapılandırılması gerektiğini ortaya koymaktadır. Modelin KBRN eğitimlerinde kullanımı, hata kaynaklarını yalnızca bireysel dikkatsizlikle sınırlamadan, örgütsel ve sistemsel düzeyde kök nedenleri tanımlamaya imkan vermektedir (Razak vd., 2023; Farhat vd., 2024).

Şekil 1 örgütsel karar hatalarından bireysel davranışlara kadar uzanan çok katmanlı bir hata zincirini temsil etmektedir. Her bir katmandaki "bariyer", sistemdeki savunma mekanizmasını simgelemektedir. Bu savunmalardan bir veya birkaçının başarısız olması, hataların ilerlemesine ve nihai olarak kazaya neden olmaktadır.

Figure 1. Turkish adaptation of the Swiss Cheese model (Adapted from Reason (2000)).
Şekil 1. *Swiss Cheese modelinin Türkçe uyarlaması (Reason (2000)'den uyarlanmıştır).*

HFACS Modeli

HFACS modeli (Human Factors Analysis and Classification System: İnsan Faktörleri Analiz ve Sınıflandırma Sistemi), insan hatalarının nedenlerini dört düzeyde incelemektedir: (i) doğrudan hatalar, (ii) koşullu etkenler, (iii) denetim eksiklikleri ve (iv) örgütsel etkiler (Li vd., 2008; Diller vd., 2014). Bu yaklaşım, KBRN eğitimlerinde karşılaşılan sorunların yalnızca uygulayıcı düzeyinde değil, sistemin planlama ve yönetim boyutlarında da ortaya çıkabileceğini göstermektedir.

Nazari vd. (2023) tarafından yapılan karşılaştırmalı analiz, KBRN sağlık müdahale ekiplerinin etkinliğinin; görev tanımlarının netliği, liderlik yapısının tutarlılığı ve iletişim zincirinin açıklığıyla doğrudan ilişkili olduğunu ortaya koymuştur. Dolayısıyla HFACS, hataları bireysel beceriksizlik yerine sistemsel eksikliklerin çıktısı olarak ele almaktadır. Gkikas vd. (2025), operasyonel risk değerlendirme süreçlerinde insan faktörlerine odaklanmanın güvenlik ve performansta sürdürülebilir iyileşmeler sağladığını bildirmiştir. Benzer bir mantığın KBRN operasyonel eğitimlerinde de uygulanmasının kalıntı riskin (residual risk) azaltılmasına katkı sunabileceği düşünülmektedir.

HFACS'in KBRN eğitimlerine entegrasyonu, hataların sistematik biçimde sınıflandırılmasını, kök nedenlerin izlenmesini ve örgütsel düzeyde geri besleme mekanizmalarının kurulmasını kolaylaştıracaktır. Böylece eğitim yöneticileri, hangi aşamada ve hangi düzeyde müdahale edilmesi gerektiğini daha açık biçimde görebilecektir (Bogdan-Ioan vd., 2024; Bearman vd., 2025).

HFACS modeli, insan hatalarını dört hiyerarşik düzeyde analiz etmektedir: (i) örgütsel etkenler, (ii) güvensiz gözetim, (iii) ön koşullar ve (iv) güvensiz davranışlar. Katmanlar arasındaki nedensel ilişkiler, hataların sistematik biçimde birikerek olay veya kaza noktasına ulaşmasını açıklamaktadır. Bu çerçevede HFACS, KBRN eğitim programlarında *"hata nerede oluştu?"* sorusundan ziyade *"bu hatayı hangi sistem bileşeni doğurdu?"* sorusuna odaklanarak, öğrenen bir organizasyon yapısının oluşumuna katkı sağlamaktadır. Böylece eğitim süreçleri yalnızca bilgi aktarımı değil aynı zamanda risk farkındalığı, karar kalitesi ve örgütsel adaptasyonun birlikte geliştirildiği dinamik bir öğrenme döngüsüne dönüşmektedir.

Figure 2. Turkish adaptation of the HFACS model (based on Wiegmann & Shappell (2001)).
Şekil 2. *HFACS modelinin Türkçe uyarlaması (Wiegmann & Shappell (2001) temel alınarak hazırlanmıştır).*

SHELL Modeli

SHELL modeli (Software–Hardware–Environment–Liveware–Liveware: Yazılım-Donanım-Çevre-İnsan-İnsan Etkileşimi), insan performansını belirleyen beş temel bileşenin etkileşimini açıklamaktadır: (i) yazılım (prosedürler ve talimatlar), (ii) donanım (ekipman), (iii) çevre (fiziksel ve örgütsel koşullar), (iv) birey (canlı unsur) ve (v) kişiler arası ilişkiler (Anderson & Boddington, 2024). Model, bu bileşenler arasındaki dengenin bozulmasının hata olasılığını artırdığını; özellikle KBRN eğitimlerinde ekipman tasarımı, prosedürel karmaşıklık, çevresel stresörler ve ekip içi iletişim arasındaki uyumsuzlukların sistem güvenliği üzerinde kritik etkiler yarattığını göstermektedir.

Son (2023), kişisel koruyucu donanım (PPE) uyumsuzluğunun görev performansını ve dayanıklılığı azalttığını belirtirken; Altan vd. (2022) kişisel donanımın ergonomik tasarımının polis eğitimlerinde denge ve hareket kabiliyeti üzerinde belirleyici rol oynadığını saptamıştır. Benzer biçimde, Son (2023) afet yönetimi operasyonlarında ergonomik sınırlılıkların ve bilişsel yükün insan performansını önemli ölçüde etkilediğini vurgulamıştır.

SHELL modeli, bu tür bulguları açıklamak için uygun bir çerçeve sunmaktadır. Modelin KBRN eğitimine uygulanması, hem teknik (donanım tasarımı, PPE uyumu) hem de insani (iletişim, koordinasyon, çevresel adaptasyon) faktörlerin eşzamanlı değerlendirilmesini sağlamaktadır (Altan vd., 2022; Son, 2023; Lee, 2025; Lucena vd., 2026). Bu bütüncül bakış, eğitim programlarının yalnızca teknik yeterliliğe değil, insan–sistem etkileşiminin kalitesine odaklanmasına olanak tanımaktadır.

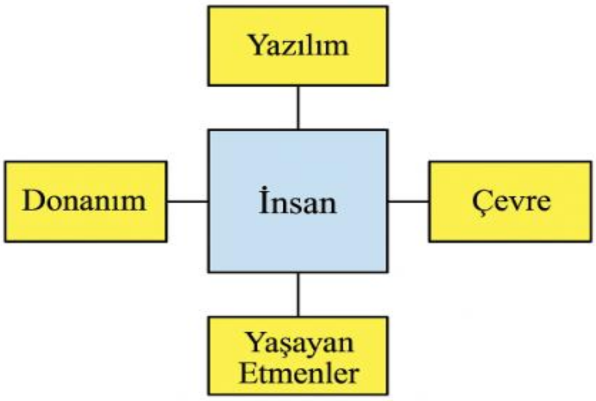

Figure 3. SHELL Model (Adapted from Hawkins (1993))

Şekil 3. *SHELL Modeli (Hawkins (1993)'ten uyarlanmıştır)*

SHELL modeli, insanı sistemin merkezine yerleştirerek yazılım, donanım, çevre ve diğer insan bileşenleri arasındaki etkileşimleri tanımlamaktadır. Model ayrıca insan performansını etkileyen ergonomik, çevresel ve psikososyal faktörlerin bütüncül biçimde analiz edilmesine olanak sağlamaktadır. Bu bağlamda SHELL modeli, KBRN eğitim sistemlerinde insan faktörleriyle ilişkili hataların kökenlerini anlamada ve eğitim tasarımlarını insan-merkezli güvenlik kültürü doğrultusunda yeniden yapılandırmada kuramsal bir temel sunmaktadır.

Modellerin Bütünleştirilmesi (Bütüncül KBRN Eğitim Yaklaşımı)

Swiss Cheese, HFACS ve SHELL modelleri, birbirini tamamlayan üç kuramsal düzlemde hata dinamiklerini açıklamaktadır. Bu üçlü yaklaşımın bütünleştirilmesi, KBRN eğitimlerinde insan, teknoloji ve örgüt etkileşimini tekil bir çerçevede analiz etmeyi mümkün kılmaktadır.

Swiss Cheese modeli, hataların savunma bariyerlerini aşarak kazaya dönüşüm sürecini sistem düzeyinde tanımlamaktadır. HFACS modeli, bu süreçteki neden-sonuç ilişkilerini hiyerarşik bir yapı içinde sınıflandırarak, hataların yalnızca bireysel değil kurumsal kökenlerini de ortaya koymaktadır. SHELL modeli ise insanın sistem içindeki konumunu, kullandığı donanım, yazılım, çevre koşulları ve diğer bireylerle olan etkileşimleriyle birlikte analiz etmektedir (Hawkins, 1993; Reason, 2000).

Bu bütünleşik yapı, KBRN eğitimlerinin yalnızca bilgi aktarımı odaklı değil aynı zamanda davranışsal adaptasyon, bilişsel yük yönetimi ve sistem güvenliği farkındalığı boyutlarını içeren çok katmanlı bir öğrenme süreci olarak tasarlanmasını sağlamaktadır. Böylece eğitim müfredatları, insan hatalarını azaltmanın ötesinde, örgütsel öğrenme, iletişim zinciri yönetimi ve operasyonel koordinasyon gibi üst düzey performans bileşenlerini de güçlendirmektedir (Razak vd., 2023; Bearman vd., 2025).

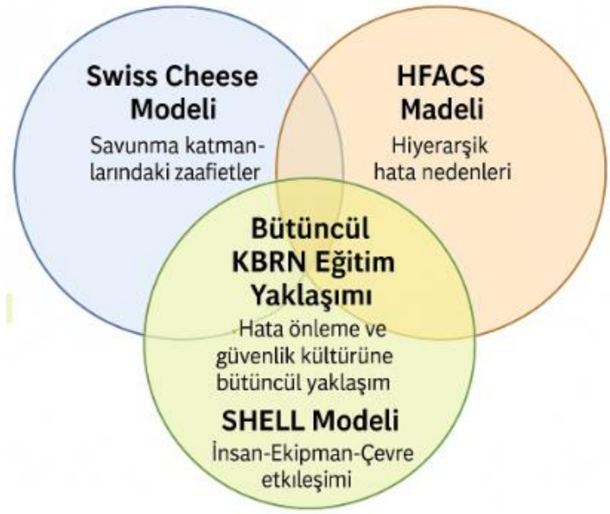

Figure 4. Holistic CBRN training approach: Swiss Cheese–HFACS–SHELL integration

Şekil 4. *Bütüncül KBRN eğitim yaklaşımı: Swiss Cheese–HFACS–SHELL entegrasyonu*

Şekil 4 üç modelin etkileşimini temsil etmektedir. Swiss Cheese modeli sistemdeki bariyer zayıflıklarını, HFACS modeli hataların hiyerarşik nedenlerini, SHELL modeli ise insan–ekipman–çevre etkileşimini göstermektedir. Bu üç bileşenin birleşimi, KBRN eğitimlerinde bütüncül bir hata önleme ve güvenlik kültürü yaklaşımı oluşturmaktadır. Bu entegrasyon, KBRN eğitimlerinde kullanılan geleneksel teknik öğretim modellerinden farklı olarak, insan faktörleri temelli risk değerlendirme ve örgütsel geri bildirim mekanizmalarını eğitim tasarımına doğrudan entegre etmektedir. Aynı zamanda dijital teknolojilerin (örneğin yapay zeka destekli karar sistemleri ve sanal gerçeklik tabanlı simülasyonlar) kullanımıyla öğrenme ortamlarının dinamik olarak izlenmesine olanak tanımaktadır (Kegyes vd., 2024; Malizia vd., 2025).

Bu çalışmada önerilen bütüncül model yaklaşımı KBRN eğitimlerinde güvenlik kültürünün sürdürülebilir biçimde güçlendirilmesi, hataların sistematik olarak izlenmesi ve insan performansının ölçülebilir biçimde optimize edilmesi için kuramsal ve pratik bir çerçeve sunmaktadır. Bu yapı, gelecekteki KBRN eğitim müfredatlarının yeniden yapılandırılmasında referans bir model olarak değerlendirilebilir.

Kuramsal entegrasyonun temel amacı, insan hatasını bireysel başarısızlık değil öğrenilebilir bir sistem çıktısı olarak değerlendirmektir (Shabani vd., 2024). KBRN eğitimlerinde bu anlayış, güvenlik yönetiminden eğitim stratejilerine kadar tüm süreçlerin yeniden yapılandırılmasına zemin hazırlamaktadır. Modelin çok katmanlı yapısı, insan faktörlerinin ölçülebilir hale getirilmesini, hataların önleyici biçimde analiz edilmesini ve gelecekteki eğitim politikalarına sistematik veri sağlamayı mümkün kılmaktadır. Bu yaklaşımla geliştirilen eğitimler, yalnızca bilgi aktarımını değil güvenli davranışın içselleştirilmesini de hedefleyen dinamik bir öğrenme ortamı yaratmaktadır. Swiss Cheese, HFACS ve SHELL modellerinin bütünleşik biçimde uygulanması KBRN eğitimlerinde hata analizine dayalı kalite güvencesi sistemlerinin geliştirilmesine ve insan merkezli güvenlik kültürünün yerleşmesine bilimsel temel sağlamaktadır.

TARTIŞMA

KBRN eğitimleri, yüksek riskli ortamlarda görev yapan personelin yalnızca teknik becerilerini değil aynı zamanda stres altında karar verme, ekip içi koordinasyon ve durumsal farkındalık gibi bilişsel yetkinliklerini geliştirmeyi hedefleyen çok katmanlı süreçlerdir. Bu süreçlerin başarısı, eğitimin içeriğinden ziyade insan–sistem etkileşimini ne ölçüde doğru biçimde modelleyebildiğine bağlıdır (Farhat vd., 2024). Özellikle insan faktörlerinin, operasyonel performansın hem belirleyicisi hem de sınırlayıcısı olduğu gösterilmiştir (Giaume vd., 2024). Bu bağlamda, literatürde tanımlanan üç temel kuramsal modelin (Swiss Cheese, HFACS ve SHELL) birlikte yorumlanması, KBRN eğitimlerinde hata oluşum mekanizmalarının çok düzeyli analizine olanak tanımaktadır (Hawkins, 1993; Reason, 2000; Wiegmann & Shappell, 2001).

Swiss Cheese modeli, hataların çok katmanlı savunma sistemleri içindeki zayıf halkalar aracılığıyla zincirleme biçimde ilerleyebileceğini göstermektedir. Ancak bu model, hataların neden bu zayıflıkların oluştuğuna dair kök nedenleri açıklamakta sınırlıdır. Bu noktada HFACS modeli, bireysel davranışlardan örgütsel süreçlere kadar uzanan bir nedensellik zincirini tanımlayarak eğitim ortamlarında ortaya çıkan hataların sistemsel kökenlerini analiz etmeye olanak tanımaktadır. Böylece, KBRN eğitimlerinde hataların sınıflandırılmasında Swiss Cheese modelinin ardından HFACS modelinin kullanılması bütüncül bir değerlendirme sağlamaktadır.

KBRN eğitimlerinin başarısızlık nedenleri çoğunlukla bireysel hatalarla açıklanmakta; ancak HFACS modeline göre bu hatalar, denetim eksiklikleri, yetersiz kaynak tahsisi, iletişim sorunları ve örgütsel kültür gibi üst düzey faktörlerin sonucudur (Wiegmann & Shappell, 2001). Nazari vd. (2023) saha düzeyinde karşılaşılan hataların büyük bölümünün açık görev tanımları ve liderlik yapısı eksikliğinden kaynaklandığını göstermektedir. Bu durum, eğitim süreçlerinin yalnızca uygulayıcı odaklı değil sistemsel olarak tasarlanması gerektiğini vurgulamaktadır. Bununla birlikte, SHELL modeli insan–ekipman–çevre etkileşimini merkeze alarak ergonomik uygunluk ve psikolojik dayanıklılığın performans üzerindeki etkilerini açıklamaktadır (Hawkins, 1993). Anderson & Boddington (2024) ile Son (2023) kişisel koruyucu ekipman kullanımının bilişsel yük ve hareket kısıtlaması yarattığını; bu nedenle hataların çoğu zaman çevresel stresörlerle ilişkili olduğunu belirtmiştir. Gkikas vd. (2025) kişisel koruyucu ekipman kullanımında fizyolojik yükün önceden öngörülebilmesi için geliştirdikleri modellerin eğitim planlamasında performans tahmini amacıyla kullanılabileceğini göstermiştir. Bu sonuçlar, SHELL modelinin eğitim tasarımında ergonomik ve bilişsel bileşenleri dengelemede etkili bir araç olduğunu kanıtlar niteliktedir.

Swiss Cheese modeli, hataların sistemin çoklu bariyerleri arasındaki boşluklardan sızma eğilimini açıklayarak eğitim sürecinin yalnızca bireysel değil yapısal zayıflıklarını da görünür kılmaktadır (Reason, 2000). Özellikle KBRN gibi karmaşık görevlerde bariyerlerin yalnızca teknik önlemlerle değil davranışsal ve örgütsel katmanlarla da desteklenmesi gereklidir (Malizia vd., 2025). Rimpler-Schmid vd. (2021) Avrupa Birliği KBRN hazırlık politikalarının çoğunda sistemsel güvenlik katmanlarının eksik tanımlandığını, bu nedenle riskin yalnızca bireysel düzeyde değerlendirildiğini vurgulamıştır. Bu eksiklik, eğitimlerin risk analizinden ziyade prosedür tekrarına indirgenmesine yol açmaktadır. Swiss Cheese modelinin KBRN bağlamında uygulanması, bu eğilimi kırarak hataları önleyici bir öğrenme kültürü geliştirmeye katkı sağlamaktadır. Son yıllarda, teknolojik yeniliklerin bu kuramsal yaklaşımlarla bütünleştirilmesi KBRN eğitimlerinde önemli fırsatlar yaratmıştır. Güncel literatürde KBRN eğitiminde kullanılan teknolojik yaklaşımlar Tablo 2'de özetlenmiştir.

Regal vd. (2023) VR tabanlı eğitim çalışmalarının senaryo tekrarının bilişsel yükü azalttığını ve hata farkındalığını artırdığını belirtmiştir. Benzer biçimde, Kegyes vd. (2024) makine öğrenmesi tabanlı karar destek sistemlerinin KBRN koruma görevlerinde riski azaltabileceğini bildirmiştir. Bu bulgular, KBRN önleme ve koruma misyonları için karar destek modeliyle uyumludur (Nemeth vd., 2024). Sistem, eğitim sırasında toplanan sensör verilerini kullanarak bilişsel yük ve karar karmaşıklığı arasında denge kurmayı amaçlamaktadır. Hancko vd. (2025) ise VR, AR ve XR sistemlerinin KBRN eğitimlerinde psikolojik stresin ölçülmesinde ve dayanıklılık geliştirilmesinde kullanılabileceğini ortaya koymuştur. Bu sonuçlar, dijital teknolojilerin yalnızca simülasyon değil aynı zamanda insan performansını izleme ve optimize etme araçları olarak işlev görebileceğini göstermektedir.

KBRN eğitimlerinin etkinliği aynı zamanda güvenlik kültürünün kurumsallaşma düzeyiyle de ilişkilidir. Abari vd. (2024) örgütsel güvenlik kültürünün, acil durum eğitimlerinin sürdürülebilirliği ve standardizasyonu için temel belirleyici olduğunu ileri sürmüştür. Benzer biçimde, Farhat vd. (2024) afet yönetimi perspektifinden inceledikleri KBRN hazırlık sistemlerinde, eğitim stratejilerinin çoğunun kısa dönemli ve reaktif olduğunu; uzun vadeli davranış değişikliğine odaklanmadığını saptamıştır. Bu bağlamda önerilen entegre KBRN eğitim modeli, sadece bireysel performans geliştirmeyi değil, örgütsel düzeyde öğrenen bir güvenlik kültürünün inşasını hedeflemektedir.

Table 2. Technological approaches used in CBRN education in current literature
Tablo 2. *Güncel literatürde KBRN eğitiminde kullanılan teknolojik yaklaşımlar*

Teknoloji	Kullanım Alanı	Uygulama Örneği	Temel Kaynak(lar)
Sanal Gerçeklik (VR)	Senaryo temelli eğitim	Gerçek zamanlı simülasyon	Regal vd. (2023)
Artırılmış Gerçeklik (AR/XR)	Psikolojik stres ölçümü	Karma ortam dayanıklılığı	Hancko vd. (2025)
Makine Öğrenmesi	Karar destek sistemi	Risk öngörüsü ve hata analizi	Kegyes vd. (2024)
Yapay Zeka Sensörleri	Fizyolojik veri takibi	Bilişsel yük ölçümü	Gkikas vd. (2025)
Exoskeleton Sistemleri	Fiziksel destek ve ergonomi	Performans artırımı	Schubert & Weidner (2025)

Çalışmada tespit edilen bulgular, KBRN eğitimlerinin geleceğinde üç temel yönelime işaret etmektedir:

(i) İnsan faktörlerinin ölçülebilir hale getirilmesi,

(ii) Teknoloji destekli öğrenme ortamlarının kurumsal sistemlerle bütünleştirilmesi,

(iii) Risk yönetimi ve ergonominin eğitim müfredatının çekirdeğine yerleştirilmesi.

Bu çerçevede, Swiss Cheese, HFACS ve SHELL modellerinin entegrasyonu yalnızca teorik bir sentez değil aynı zamanda sahada uygulanabilir bir değerlendirme aracı olarak önerilmektedir. Entegre yaklaşım, hem insan performansına dayalı risk azaltımını mümkün kılmakta hem de karar destek sistemleriyle bütünleştiğinde sürdürülebilir güvenlik kültürünün temellerini güçlendirmektedir.

SONUÇ VE ÖNERİLER

Bu çalışma, KBRN eğitimlerinde insan faktörlerinin ergonomik koşulların ve sistemsel etkileşimlerin bütüncül biçimde değerlendirilmesi gerektiğini ortaya koymuştur. Literatür ve model analizleri, hata oluşumunun yalnızca bireysel yetersizliklerle açıklanamayacağını; organizasyonel süreçler, çevresel koşullar ve teknolojik faktörlerin de belirleyici rol oynadığını göstermektedir (Nazari vd., 2023; Farhat vd., 2024). Özellikle Swiss Cheese, HFACS ve SHELL modellerinin bütünleştirilmesiyle geliştirilen entegre KBRN eğitim modeli, hata analizini çok düzeyli bir yapı içinde ele alarak sistem güvenliğini insan performansının ayrılmaz bir parçası haline getirmiştir.

Araştırma sonuçları, KBRN eğitimlerinin etkililiğinin yalnızca bilgi aktarımı veya prosedürel tekrarlarla sınırlı kalmaması gerektiğini; bunun yerine bilişsel yük yönetimi, karar destek mekanizmaları ve ergonomik optimizasyonun birlikte ele alınmasının zorunlu olduğunu göstermektedir (Son, 2023; Anderson & Boddington, 2024). Özellikle PPE kullanımına ilişkin ergonomik zorluklar, görev süresince artan fiziksel ve bilişsel yük nedeniyle operasyonel hataların temel kaynağı haline gelebilmektedir (Gkikas vd., 2025; Lucena vd., 2026). Eğitim süreçlerinde bu faktörlerin ölçülebilir biçimde izlenmesi, performans düşüşlerinin erken tespit edilmesini ve önleyici müdahalelerin uygulanmasını kolaylaştıracaktır.

Çalışmanın bir diğer önemli bulgusu, teknolojik araçların KBRN eğitimlerinde yalnızca simülasyon değil aynı zamanda ölçme–değerlendirme ve geribildirim sistemi olarak kullanılabileceğini ortaya koymasıdır. Sanal gerçeklik (VR) ve karma gerçeklik (XR) uygulamaları, eğitimi güvenli bir laboratuvar ortamına dönüştürürken; makine öğrenmesi ve karar destek sistemleri, performans verilerinin nesnel biçimde analiz edilmesine olanak tanımaktadır (Regal vd., 2023; Kegyes vd., 2024; Nemeth vd., 2024). Bu teknolojilerin, SHELL modelinde tanımlanan insan–donanım etkileşimi boyutuna entegre edilmesi hem bireysel öğrenme hızını artırmakta hem de hataların kök neden analizini kolaylaştırmaktadır.

KBRN eğitimlerinde sistem güvenliği kadar örgütsel güvenlik kültürünün güçlendirilmesi de gerekmektedir. HFACS ve Swiss Cheese modelleri, hataların önlenmesinde yalnızca bireylerin değil kurumların da sorumluluk taşıdığını vurgulamaktadır (Zavila, 2025). Bu nedenle kurumların standart operasyon prosedürlerini, liderlik yapısını ve iletişim zincirini açık biçimde tanımlaması, eğitim çıktılarının sürekliliği için kritik önem taşımaktadır (Rimpler-Schmid vd., 2021; Abari vd., 2024). Eğitim programları, yalnızca olay tepkisi değil aynı zamanda öğrenen organizasyon yapısının inşası amacıyla tasarlanmalıdır.

Sonuç olarak, bu çalışma KBRN eğitimlerinde disiplinler arası bir yaklaşımın gerekliliğini vurgulamaktadır. İnsan faktörleri, ergonomi, psikoloji ve sistem mühendisliği temelli modellerin entegrasyonu, gelecekte KBRN hazırlık stratejilerinin bilimsel temelini oluşturacaktır. Bu çerçevede üç temel öneri geliştirilebilir:

- *Model temelli eğitim sistemleri:* Swiss Cheese, HFACS ve SHELL modelleri entegre edilerek hata önleme odaklı ve davranış temelli müfredatlar geliştirilmelidir.
- *Veri temelli karar destek araçları:* Yapay zeka tabanlı izleme ve analiz sistemleri, eğitim performansını nesnel biçimde

değerlendirmek için etkin biçimde kullanılmalıdır.

- *Sürdürülebilir güvenlik kültürü:* Eğitimler, bireysel becerilerin ötesinde, kurumsal öğrenme kapasitesini ve davranışsal güvenliği kalıcı biçimde güçlendirmelidir.

Bu bütüncül yaklaşım, KBRN eğitimlerinin yalnızca reaktif değil öngörülü ve dayanıklı sistemlere dönüşmesine katkı sağlayacaktır. Böylelikle gelecekteki KBRN olaylarına müdahalelerde hem bireysel hem de kurumsal düzeyde daha yüksek bir hazırlık ve güvenlik standardı oluşturulabilecektir.

TEŞEKKÜR

Bu çalışmanın hazırlanmasında bilimsel bilgi ve tecrübeleriyle bize rehberlik eden, araştırma sürecinin her aşamasında değerli katkılarını esirgemeyen İskenderun Teknik Üniversitesi Lisansüstü Eğitim Enstitüsü KBRN Anabilim Dalı'nın değerli akademik ve idari personeline şükranlarımızı sunarız. Bu süreçte doğrudan ya da dolaylı olarak katkı sağlayan tüm kişi ve kurumlara teşekkür ederiz.

Etik Standartlara Uygunluk

Yazar Katkısı

AÖ: Kavramsallaştırma, Gözetim ve denetim, Yöntem geliştirme, Doğrulama, Biçimsel analiz, Veri küratörlüğü

AÇ: Araştırma, Materyal sağlama, Görselleştirme, Yazma – orijinal taslak hazırlama, Yazma – inceleme ve düzenleme

Tüm yazarlar makalenin son halini okumuş ve onaylamıştır.

Çıkar Çatışması

Yazarlar herhangi bir çıkar çatışması olmadığını beyan etmektedir.

Etik Onay

Yazarlar bu çalışma için resmi etik kurul onayının gerekli olmadığını bildirmektedir.

Finansal Destek

Yazarlar bu çalışma için herhangi bir finansal destek almadıklarını bildirmektedir.

Veri Kullanılabilirliği

Yazarlar bu çalışmanın bulgularını destekleyen verilerin makale içinde mevcut olduğunu onaylamaktadır.

Yapay Zeka Açıklaması

Bu makalenin yazım ve revizyon sürecinde, yalnızca dilbilgisi kontrolü, biçimsel düzenleme ve kaynak doğrulama amaçlarıyla yapay zeka destekli metin denetim araçlarından (örneğin ChatGPT) yararlanılmıştır. Bilimsel içerik, yorumlama, sonuç ve öneriler tamamen yazarlar tarafından geliştirilmiştir. Yapay zeka araçları, veri üretimi, literatür analizi veya özgün bulgu oluşturma süreçlerinde kullanılmamıştır.

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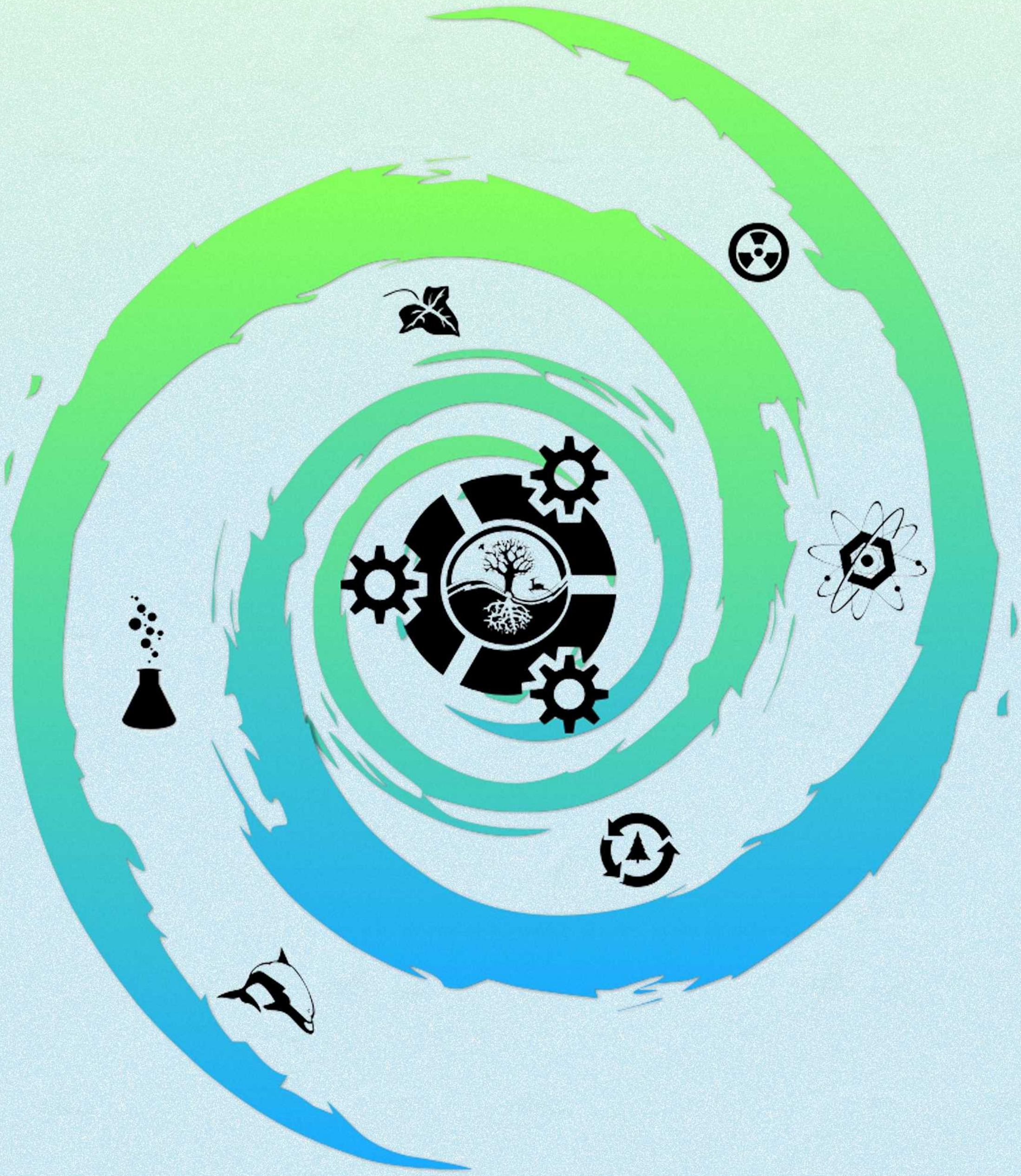

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