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Artificial Intelligence Applications in the Aquaculture Industry: Sustainability, Efficiency and Innovative Solutions

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Abstract: Artificial Intelligence (AI) is becoming increasingly important to increase efficiency and sustainability by organizing processes and providing significant improvements in different sectors. AI is reshaping the aquaculture sector. AI is being used to help solve optimization problems in aquaculture, reduce costs, and find sustainable solutions. These scenarios guided the evaluation of the future role of AI in aquaculture and the benefits that AI brings to the aquaculture sector in this study. AI is improving the way fish stocks are monitored, live stocks are assessed, diseases among plants and animals are recognized, water quality is tested, and production lines are controlled. Aquaculture uses AI technologies to help detect diseases early, monitor environmental conditions affecting production, and improve both efficiency and sustainability. In addition, AI is examining and providing solutions to environmental issues such as global warming and water resource management.

Keywords: Aquaculture, Sustainability, Artificial intelligence

Su Ürünleri Endüstrisinde Yapay Zekâ Uygulamaları: Sürdürülebilirlik, Verimlilik ve Yenilikçi Çözümler

Özet: Yapay Zekâ (YZ), süreçleri organize ederek ve farklı sektörlerde önemli gelişmeler sağlayarak verimliliği ve sürdürülebilirliği artırmak için giderek önemli bir hale gelmektedir. YZ, su ürünleri yetiştiriciliği sektörünü yeniden şekillendirmektedir. YZ, su ürünleri yetiştiriciliğinde optimizasyonla ilgili sorunları çözmeye, maliyetleri düşürmeye ve sürdürülebilir çözümler bulmaya yardımcı olmak için kullanılmaktadır. Bu senaryolar, bu çalışma kapsamında YZ'nın su ürünleri yetiştiriciliğindeki gelecekteki rolünün ve YZ'nın su ürünleri yetiştiriciliği sektörüne sağladığı faydaların değerlendirilmesine rehberlik etmiştir. YZ, balık stoklarının izlenmesi, canlı stokların değerlendirilmesi, bitkiler ve hayvanlar arasındaki hastalıkların tanınması, su kalitesinin test edilmesi ve üretim hatlarının kontrol edilmesi şeklini geliştirmektedir. Hastalıkları erken tespit etmeye, üretimi etkileyen çevre koşullarını izlemeye ve hem verimliliği hem de sürdürülebilirliği iyileştirmeye yardımcı olmak için su ürünleri yetiştiriciliği YZ teknolojilerini kullanmaktadır. Ayrıca, yapay zekâ küresel ısınma ve su kaynaklarının yönetimi gibi çevreyi etkileyen sorunları incelemekte ve bu konulara çözümler sunmaktadır.

Anahtar Kelimeler: Su ürünleri, Sürdürülebilirlik, Yapay zekâ

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1. Introduction

In today's rapidly evolving technological world, AI is a powerful tool for enhancing processes in various application areas (Rashid et al., 2024). AI is successfully applied in data analysis, prediction, learning, and decision-making tasks by operating the information-processing processes of the human brain (Ahmed et al., 2022). AI has become remarkable in the aquaculture industry because it delivers optimal and creative solutions in numerous application areas that can surpass the disadvantages of conventional techniques.

Artificial intelligence can be defined as the simulation of human intelligence in a machine that can learn, solve problems, reason, make decisions, understand language, and even recognize faces (Zhang and Lu, 2021). Artificial intelligence relativity can learn from data and further utilize this learning in its future trend. AI can arrive at a decision given several inputs by creating recognizable relationships between the pieces of information. With current systems that operate on artificial intelligence, it is possible to incorporate natural language processing technologies. Intelligent systems can convert figures and symbols, such as images and sound, into comprehensible formats for the system's output and are also capable of pattern analysis through the analysis of large data formations (Gupta et al., 2021). For these reasons, artificial intelligence can be considered a crucial technology among others, most notably in industries with data-driven and complex structures, such as aquaculture.

Aquaculture is relied on by an estimated 1 billion people, providing food, livelihoods, and revenues for billions worldwide (Ahmad et al., 2021). For this reason, it calls for sustainable and efficient approaches. However, environmental, economic, and technical factors constrain such progress, hence imposing the need for unique and better technologies. AI offers affordable and practical solutions for the aquaculture industry to enhance the flow of production processes, particularly in light of environmental degradation (Mustapha et al., 2021).

The application of artificial intelligence in aquaculture encompasses population tracking, disease identification in plants and animals, water quality monitoring, and productivity estimation (Gladju et al., 2022). While image processing algorithms identify species using images captured by underwater cameras and drones, deep learning models can help improve production planning by modeling fish growth rates about environmental conditions and enhancing product quality through better resource utilization (Zhao et al., 2025).

Another factor relating the aquaculture industry to sustainability is that the industry relies on natural resources (Engle et al., 2022). AI solutions can be applied for environmental purposes. They can be used to reach objectives such as limiting the fishing industry, ending deforestation, and lowering CO_2 emission levels. They can provide economically viable solutions while also having ecological significance (Rodriguez and Costa, 2024).

Diseases are one of the most significant factors affecting the production rate in the aquaculture industry. Islam et al. (2024) reveal that the application of artificial intelligence aids in the diagnosis and control of diseases in fish and other aquaculture species. As with other applications, image processing models input images of fish skin and diagnose infection within record time (Bohara et al., 2024). Given that the process of aquaculture is based on continually evolving environmental and biological indicators, the application of artificial intelligence models studies the impact of certain factors such as water temperature, salinity, and level of dissolved oxygen on production, which, in turn, makes it possible to make appropriate decisions and return production processes to a predictable, designated pattern (Ahmad et al., 2024).

Global warming and climate change are among the most significant risks facing the aquaculture industry. Climate change has become a primary concern for several countries and regions, as evidenced by the increasing use of AI in assessing its impacts (Yadav et al., 2024). Over the years, the impact of climate change on fisheries and aquaculture, as well as methods to mitigate these effects, have been learned from long-term data. However, another benefit that can be obtained from using artificial intelligence in the aquaculture industry is the formation of economic value. The benefits of AI to the industry's commercial advantage include raising efficiency levels in the manufacturing process, increasing output, reducing expenses, and meeting market demand (Mustapha et al., 2021). Unlike previous reviews that focus solely on technical AI advancements or aquaculture systems separately, this study presents an integrated and up-to-date perspective by systematically mapping AI applications in aquaculture with an emphasis on sustainability, climate adaptation, and real-world deployment gaps.

2. Methodology

This article adopts a systematic literature review methodology to explore the applications of AI in the aquaculture industry. Peer-reviewed publications between 2015 and 2025 were retrieved from well-established academic databases, including Scopus, Web of Science, IEEE Xplore, and Google Scholar. The search was conducted using keyword combinations such as artificial intelligence, machine learning, deep learning, aquaculture, fish farming, sustainability, and precision aquaculture. The inclusion criteria were relevance to AI applications in aquaculture, empirical or practical contribution to the field, publication in English, and peer-reviewed status. Studies unrelated to aquatic environments or focusing solely on theoretical AI development were excluded. After removing duplicates and filtering non-relevant papers, 78 articles were selected for detailed review. These articles were categorized into thematic areas, including water quality monitoring, population tracking, disease detection, production optimization, logistics, sustainability, and challenges. The selected works were then critically analyzed in terms of methodological approaches, application levels, and practical relevance to industry needs.

3. Aquaculture

Aquaculture refers to the cultivation of aquatic organisms, including fish, crustaceans, mollusks, and aquatic plants, under controlled conditions (Verdegem et al., 2023). The rapid increase in global population, the decline in terrestrial agricultural areas due to urbanization, and the pressures exerted by hunting on natural fish stocks have led to production that reaches the limits of sustainability through hunting. Aquaculture practices, which can be carried out in both marine and freshwater environments, reduce pressure on natural stocks and contribute to economic development in rural areas. Aquaculture, the fastest-growing sector in the world today, meets a significant portion of the global population's protein needs and is an integral part of sustainable development (Rakkannan and Agarwal, 2025). Aquaculture plays a crucial role in seafood production by providing a sustainable solution to the increasing global food demand. According to FAO 2022 data, global aquaculture production has reached approximately 120 million tons per year, accounting for more than 50% of total aquaculture consumption (Dongyu, 2024). In Turkey, according to the 2023 reports of the Ministry of Agriculture and Forestry, the sector generates export revenues of over $ 1.5 billion, with aquaculture exceeding 500,000 tons per year (Dirican, 2024).

Providing significant contributions in terms of food security, employment, and exports, aquaculture supports the access of approximately 1 billion people worldwide to a basic source of protein (Dewali et al., 2023). Aquaculture projects are emerging as a key component in the development of rural areas and the fight against poverty in developing countries. Developments in the aquaculture sector worldwide have also shown themselves in our country, which is surrounded by seas on three sides (Verdegem et al., 2023). Turkey's geographical location and existing natural resources offer suitable opportunities for fishing and aquaculture. In particular, trout farming in the Black Sea and sea bream-sea bass farming in the Aegean and Mediterranean are the locomotives of the sector. In recent years, new investments, such as shrimp farms in Muğla and Antalya and mussel farms in İzmir, have come to the fore. In inland waters, facilities that produce high-yield trout with closed circuit systems (RAS) are making Turkey progress towards becoming one of the largest aquaculture centers in Europe (Brown et al., 2024).

However, this growth also carries ecosystem risks in the event of uncontrolled expansion. For example, excessive feed use and waste accumulation can hurt water quality. Therefore, biofilter systems and regular water quality monitoring protocols are of vital importance (Pachaiappan et al., 2022). On the other hand, properly planned aquaculture projects can prevent migration by creating employment in rural areas. Sea bream-sea bass farms in Muğla contribute to socio-economic development by providing employment opportunities for thousands of people in the region.

Aquaculture is a rapidly growing sector both globally and in our country. Increasing seawater temperatures due to climate change necessitate a reshaping of aquaculture strategies. Solutions such as orientation towards cold-water species or deep-sea cage systems are on the agenda for adaptation. Within the scope of the EU Green Deal, it is anticipated that facilities with sustainable certification will gain an advantage in exports (Faichuk et al., 2022). The number of ASC (Aquaculture Stewardship Council) certified farms in Turkey is also increasing every year. The issue of why aquaculture is important and its relationship with sustainable development in this context is primarily related to the food problem that is likely to be experienced in the future. The world population is expected to increase to 9.6 billion by 2050, resulting in a substantial demand for food and protein sources (Messina, 2022). Today, fish and fish products provide a significant portion of daily animal protein intake in many developing countries.

Sustainability in aquaculture practices is achieved in line with the goals of reducing environmental impact, protecting biodiversity, and ensuring long-term production efficiency (Troell et al., 2023). Applications such as increasing feed efficiency, reducing antibiotic use, and wastewater treatment are critical for environmentally friendly production. At the same time, certified production systems enhance consumer confidence and promote sustainable production practices. For example, closed-circuit aquaculture systems (RAS) provide up to 90% water savings compared to traditional methods while minimizing environmental impact through effective waste control (Shitu et al., 2022). Thanks to advances in feed technology, the use of insect protein and microalgae instead of fish meal reduces the ecological footprint of the sector.

Production efficiency and animal health are directly dependent on the quality of water. Parameters such as temperature, dissolved oxygen, pH, and ammonia levels are constantly monitored in aquaculture enterprises

(Prapti et al., 2022). In this way, stress factors can be detected early, and intervention can be made possible. Advanced sensor systems and automation technologies have made the production process more controlled and reliable.

4. Applications of Artificial Intelligence in the Aquaculture Industry

Aquaculture is being significantly transformed by AI, which is helping to make farming smarter, more efficient, and more sustainable at different stages. This section provides a step-by-step review of AI applications in aquaculture and the ways AI is helping to modernize the sector.

4.1. Water quality analysis

Using AI, real-time assessments and predictions of key water properties, such as temperature, pH, dissolved oxygen, and ammonia, are possible. The combination of sensors and machine learning enables the detection of anomalies earlier, allowing the system to send signals to the farm manager immediately. This approach reduces the risk of fish kills and promotes quality environments in aquatic systems (Bibri et al., 2024; Capetillo-Contreras et al., 2024). Predicting environmental trends is possible thanks to historical environmental data used to train predictive models that encourage early and positive actions to protect the environment (Grewal et al., 2024; Hanoon et al., 2021). AI systems utilize sensor data collected in real-time to monitor properties such as water clarity, chemical conditions, and nutrient levels in aquaculture farms. Specific patterns become apparent only when ensemble models, such as neural networks or Random Forests, indicate that the input is deviating from the optimal range. Early warning prevents ammonia from harming fish and disturbing the environment.

Additionally, AI systems utilize weather information and water flow data from rivers to detect sudden changes, such as floods or heatwaves. By predicting future needs, facilities can efficiently control filtration, aeration, and water exchange, reducing stress on the ecosystem and energy costs. They contribute to providing accurate and lasting benefits for the aquaculture industry. Most models have been studied so far only in controlled situations and have not been validated in real fish farms.

4.2. Population monitoring and species identification

Using AI, cameras, and drones are used to track fish underwater to determine the species present. Classification systems use the physical characteristics and movements of fish, including their size, color, and movements (Congdon et al., 2022; Alam et al., 2024). Automating this process helps to more accurately assess current stocks, reduce human errors, and protect endangered species (Gebremedhin et al., 2021; Ullah et al., 2024). AI models can recognize species and also show how populations are increasing or decreasing over time. In combination with YOLO and Mask R-CNN, video input is used to calculate the location and biomass of fish in the water. Such technology helps protect various species, control fisheries catches, and manage marine conservation areas.

What is more, they make it possible to monitor fish at all times without disturbing them as much as previous sampling methods. When used in conjunction with geospatial analysis, AI helps identify changes in the way animals move or reproduce in response to environmental changes. While taxonomic identifications are helpful, the approaches depend on the availability of sharp imagery, which can be challenging to obtain in some waters.

4.3. Disease detection and management

Catching diseases early is crucial in aquaculture. AI models look at images and movement patterns to detect health problems early and help stop their spread. In recent studies (Bohara et al., 2024; Hatzilygeroudis et al., 2023; Kumar et al., 2024), variables such as temperature, the number of people living in a place, and water quality can be used in conjunction with deep learning algorithms to predict outbreaks. CNNs are used in advanced systems to identify visual signs of disease from fish images very accurately. Sometimes, AI trained on large sets of infected and healthy fish performs faster and moves more smoothly than human diagnosticians. Using these resources helps lead to early intervention, stop losses, and reduce medication use. The ability to look at behavior and conditions could allow AI to identify hidden stress or risk of early infection by identifying nutritional deficiencies, unusual movements, or increased gill ventilation. Combined with genomic or microbial testing, such data could lead to better healthcare. It is often tricky for AI models to be portable across species and locations because the data available today is not well organized or diverse enough.

4.4. Optimization of production processes

AI utilizes models to determine the optimal times to harvest and feed fish based on genetic, environmental, and nutritional history information. Thanks to these models, feeding systems use less food, waste is reduced, and the products produced are of higher quality. In other words, AI can detect slow growth caused by insufficient feed and suggest steps to solve the problem (Zhang et al., 2023; Mandal and Ghosh, 2024; Capetillo-Contreras et al., 2024; Nagothu et al., 2025). AI utilizes various information, including temperature, stocking density, feed composition, and lighting cycles, to advise users on the optimal daily actions for achieving better biomass results. More often, reinforcement learning is used to mimic feeding practices and predict outcomes over time. With this approach, producers reduce their environmental impact by wasting less feed and minimizing energy and nutrient discharge. With Aquaculture Insights, precision farming becomes possible by adjusting resources according to the fish's current needs. Although optimization models have yielded positive results, very few of them are used in commercial software used by fish farmers.

4.5. Supply chain and logistics optimization

AI assists in supply chain tasks by providing more accurate demand forecasting, optimizing routes, and managing cold zones in logistics. Using machine learning, past sales, and seasonal trends are examined to predict future sales, which helps the business avoid excessive stock losses (Elufioye et al., 2024; Galaz et al., 2021). To guarantee good transport conditions for the animals and their products, AI watches over water temperature and oxygen levels during live fish delivery (Pajic et al., 2024; Anwar et al., 2023; Sohail et al., 2018). Through IoT devices, real-time monitoring of logistics conditions is easier with the aid of AI. Experience tells us that monitoring dissolved oxygen, water salinity, and vibration helps detect any potentially hazardous changes before they can harm the livestock. In addition, using AI and blockchain makes it possible to trace the entire process the fish undergoes, from where it is farmed to when it is sold. Thus, the situation helps the company meet regulations and identify any issues or risks associated with its distribution of goods. Nonetheless, large-scale, go-live applications are still necessary to truly demonstrate the effectiveness of such approaches in various logistics scenarios.

4.6. Sustainability and adaptation to climate change

AI is helping to protect the environment by identifying the effects of climate change on water. It forecasts changes in water temperature, salt levels, and acidity and suggests when and how fish will migrate and reproduce. Applying these findings facilitates the design of adaptive strategies and reduces the CO2 footprint from aquaculture, thereby helping aquaculture align with global climate goals (Goodwin et al., 2022; Mugwanya et al., 2022; Parab et al., 2023; Ditria et al., 2022; Fu et al., 2024). Simulations using artificial intelligence can help study how climate change impacts marine life and support the development of farming methods that are more resilient to climate change. In some cases, ensemble models display simulations of new habitats and suggest suitable areas to grow various crops. When combined with environmental devices, AI enables the monitoring of carbon emissions, enhances waste disposal, and assesses the impact of a business on the environment. Such knowledge supports the creation of sustainable certification programs that align with global rules, such as the EU Green Deal. Despite progress in climate modeling using AI, very few works connect the predictions from AI with real actions in the aquaculture industry.

4.7. Industry-specific challenges and opportunities

Although there are benefits, the use of AI in aquaculture is limited by high costs, inadequate facilities, and insufficient digital training for those involved. The field of agriculture is exploring new ways to utilize automation, precision farming, and enhance decision-making (Mustapha et al., 2021; Engle et al., 2022). A challenge in adoption is that hardware systems do not use consistent data formats for integration. A significant number of aquaculture businesses lack the expertise to handle the results generated by AI or operate sophisticated computer systems. Due to these challenges, interfaces and training courses should be designed in a manner that allows everyone to follow them. The use of low-cost sensors and cloud-based analytics is making it easier for more people to utilize AI. Together with universities and startups working in agri-tech, the firms have improved and accelerated solutions that take into account regional species, weather, and infrastructure. Additionally, very few solutions exist just for smallholder farmers in resource-poor areas.

4.8. Advantages and limitations of AI applications

AI enables high accuracy and instant analysis, reducing potential human errors. Artificial intelligence can enable businesses to make faster decisions and improve resource utilization (Zhang and Lu, 2021; Gupta et al., 2021). How explainable our models are is still a critical consideration. Although deep learning models can predict results with great accuracy, their complex results often cause users to doubt the decisions. Now, regulatory agencies are demanding greater transparency from companies, particularly in AI decisions involving animals or environmental safety. Some parts of the world suffer from a lack of data because the sensor network infrastructure is not fully complete. Although transfer learning and generating synthetic data are promising, they require further study and validation. Many studies suffer from using models that are difficult to explain, which leads to concerns about applying them in practice.

4.9. Future research directions

Future research in AI-aided aquaculture should focus on explainable AI (XAI), federated learning for data privacy, the integration of multimodal datasets (e.g., sensor, image, genomic), and the development of hybrid models. Additionally, affordability, accessibility, and user-friendly interfaces should be prioritized to facilitate adoption among smallholder farmers and in developing regions (Ullah et al., 2024; Rashid and Kausik, 2024). Moreover, interdisciplinary collaboration is crucial for bridging the gaps between aquaculture experts, data scientists, and policymakers. Research into the ethical implications, data ownership, and ecological impact assessments will become increasingly important as AI systems assume more autonomous roles in the industry. Pilot projects and case studies documenting real-world deployments of AI systems in aquaculture, particularly in diverse geographical contexts, are also necessary to inform best practices, policy, and investment decisions in the sector. While many future directions are proposed, a lack of interdisciplinary collaboration often hinders practical innovation and field application.

5. Practical Recommendations for the Aquaculture Industry

Based on the reviewed literature, several actionable recommendations can be proposed to guide the practical integration of AI technologies in the aquaculture sector. Start with scalable, low-cost AI solutions such as feed optimization and water quality sensors to lower entry barriers, especially for small and medium-scale farms. Invest in training and digital literacy programs to empower aquaculture professionals to effectively understand, deploy, and maintain AI systems. Public-private partnerships should be encouraged to test real AI projects and create useful use cases. Data-sharing standards should be established to support the development of higher-quality datasets, enabling the creation of reliable models for various tasks. XAI research should be continued to ensure that decisions made by models can be understood and used by those who manage the industry. Aquaculture worldwide benefits from better sustainability, improved efficiency, and increased resilience. Therefore, authorities and regulators should be involved in establishing clear guidelines for the ethical use of AI technologies in aquaculture. Such frameworks should address issues such as data ownership, accountability for decisions made by machines, and the security of personal data related to farming. At the same time, tax breaks, grants, and subsidized AI options can encourage more regions to adopt AI, especially in developing countries. Another important aspect is the involvement of fishery stakeholders, such as fish farmers, technicians, and aquaculture engineers, in the design and development of AI tools. Involving stakeholders during design and testing ensures that AI applications will reflect their needs, making them subsequently reliable and usable. For AI to be used globally, interfaces need to be in different languages , and examples need to be localized. As time passes, the use of cloud and real-time AI systems can help farmers utilize predictive technology, remotely monitor operations, and automatically control various tasks. Deciding on innovative aquaculture ecosystems will depend on robust cyber-physical systems that incorporate IoT and data security systems. Academic, industry, and policy organizations must collaborate to establish the appropriate digital infrastructure and management systems. The ethical and environmental dimensions of AI integration must not be overlooked. AI should be leveraged to support biodiversity conservation, minimize resource overuse, and reduce environmental externalities such as water pollution and carbon emissions. Models that incorporate multi-objective optimization balancing economic yield with ecological impact will be crucial in aligning aquaculture practices with the principles of sustainable development.

6. Conclusion

In this paper, five AI technologies namely machine learning, deep learning, image processing, sensor-based decision systems, and predictive analytics were reviewed in terms of their functionality in aquaculture, and the benefits of their application were discussed. The benefits of artificial intelligence include improved productivity and decreased costs, as long as the new areas for doing business and the enhancement of the innovation environment contribute to the economic development of the aquaculture business. The use of artificial intelligence in the aquaculture industry relates to the economic impact, environmental gains, and conservation.

AI is used in aquaculture to track fish, diagnose fish diseases, examine water quality, enhance production, and efficiently utilize resources and sustainability. Underwater captured images are analyzed by artificial intelligence to determine the type of fish and population growth. As a result of using image processing algorithms, one obtains fast and accurate results, reducing the number of mistakes made by humans, thus solving problems related to the environment, such as overfishing and destroying habitats, and promoting sustainability. AI can be used in the early detection of diseases affecting fish and aquatic plants, helping to minimize potential production losses and improve the overall health of aquatic organisms.

By studying how environmental conditions influence fish growth, AI can inform operations and enhance fish production. For example, sensors utilizing AI predictive models can quickly indicate whether water temperature, oxygen, or salinity levels are correct, allowing production lines to run smoothly. Smart techniques help minimize any environmental burden in the aquaculture market. Thanks to AI, fishing now has a significantly reduced impact on the planet and the fish population. This technology is crucial for detecting and mitigating climate change and temperature fluctuations in water.

For practitioners in the aquaculture industry, this study highlights several actionable lessons. The implementation of low-cost AI tools such as real-time water quality monitoring, early disease detection, and predictive feeding systems can significantly improve efficiency and reduce operational costs. Moreover, integrating explainable AI models and developing user-friendly interfaces are essential to foster trust and adoption, especially in small to mid-scale farms. Collaborations with tech developers and academic institutions can accelerate the deployment of AI systems tailored to regional and species-specific needs.

In the context of Türkiye, future studies can explore the development and deployment of region-specific AI models tailored to species such as sea bream, sea bass, and trout, which dominate the country's aquaculture industry, with a focus on local environmental conditions and infrastructure capacities.

7. Compliance with Ethical Standard

a) Author Contributions

1. E.D.B.U.: Conceptualization, methodology, software development, validation, formal analysis, investigation, resource collection, writing—original draft preparation, writing—review and editing.
2. B.K.: Conceptualization, methodology, supervision, validation, formal analysis, data curation, writing—review and editing, visualization.

b) Conflict of Interests

There is no conflict of interest, according to the authors.

c) Statement on the Welfare of Animals

Not relevant

d) Statement of Human Rights

There are no human subjects in this study.

e) Funding

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f) Artificial Intelligence Statement

During the preparation of this manuscript, the authors utilized artificial intelligence-based tools for language refinement, grammar correction, and assistance in improving the clarity and fluency of the text. All intellectual content, ideas, data interpretation, and critical insights were developed and finalized by the authors themselves. The AI tools did not contribute to scientific reasoning or experimental design.

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