



The Role of Artificial Intelligence Used in Plant Science: A Review

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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ABSTRACT

The integration of artificial intelligence (AI) technologies into plant science has emerged as a transformative force, revolutionizing various aspects of plant research, agriculture, and environmental sustainability. This paper explores the accelerating adoption and diverse applications of AI in plant science. AI techniques, including machine learning, deep learning, and computer vision, are being leveraged to enhance plant phenotyping, crop monitoring, disease detection, and yield prediction with unprecedented accuracy and efficiency. Furthermore, AI-driven approaches are facilitating the optimization of crop breeding strategies, crop management practices, and resource allocation, thereby contributing to improved agricultural productivity and resilience in the face of climate change and global food security challenges. Moreover, AI-based models are aiding in the discovery of novel plant traits, genetic markers, and biochemical pathways, accelerating the development of stress-tolerant and high-yielding crop varieties. However, challenges such as data availability, model interpretability, and ethical considerations underscore the need for continued interdisciplinary collaboration and ethical guidelines to harness the full potential of AI in plant

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science responsibly. Looking ahead, the convergence of AI with other emerging technologies like robotics, remote sensing, and genomic editing promises even greater strides in understanding and manipulating plant biology for sustainable agriculture and environmental stewardship.

Keywords: Artificial intelligence; plant science; machine learning; crop monitoring; agriculture; sustainability.

1. INTRODUCTION

Artificial Intelligence (AI) has transcended its conventional boundaries, permeating diverse sectors and leaving a profound impact on industries worldwide. Among these, the field of plant science stands out as a fertile ground where AI's transformative capabilities are reshaping traditional paradigms. The integration of AI into plant science epitomizes innovation, offering novel solutions to long-standing challenges in agriculture, ecology, and environmental sustainability [1].

Scope of plant science and its importance:

Plant science encompasses a wide range of disciplines, including molecular biology, genetics, ecology, and agronomy. At its core lies the intricate interplay between plants and their environment, which involves factors such as:

- Growth and development
- Response to environmental stressors
- Interactions with other organisms

Understanding these complex dynamics is crucial for addressing critical global issues such as:

- Enhancing crop productivity
- Ensuring food security
- Mitigating the impacts of climate change

The integration of AI has catalyzed a revolution in plant science, unlocking new avenues for research, discovery, and application [2].

AI's role in analyzing complex plant biology:

AI's capabilities in data analysis, pattern recognition, and predictive modeling offer a powerful toolkit for deciphering the complexities of plant biology and ecosystem dynamics [3]. The specific applications of AI in plant science include:

- Machine learning algorithms: Used for analyzing large datasets and revealing hidden patterns

- Neural networks: Applied for understanding relationships in plant physiology
- Big data analytics: Helps in comprehending adaptation strategies of plants under various environmental conditions

These AI-driven tools allow researchers to derive insights that are pivotal for advancing knowledge of plant growth, physiology, and adaptation strategies.

AI in crop management and agricultural optimization:

One of the most compelling applications of AI in plant science is in the realm of crop management and agricultural optimization. With the global population projected to reach 9 billion by 2050, the demand for food, feed, and fiber will increase significantly, placing unprecedented pressure on agricultural systems [4]. AI-enabled technologies offer a paradigm shift in agriculture by enabling:

- Precision agriculture: Integration of sensors, drones, and satellite imagery with AI algorithms to monitor crop health, optimize resource allocation, and reduce environmental impacts.
- Precision irrigation and fertilizer management: AI optimizes water and nutrient usage, improving crop yield and reducing waste.
- Automated pest control and robotic harvesting: These technologies enhance agricultural efficiency, minimize input costs, and reduce labor demands [5].

1. AI in Plant Breeding and Genetic Improvement AI also holds immense promise in the field of plant breeding and genetic improvement. Traditional breeding methods involve years of meticulous selection and experimentation, but AI-driven analytics and genomic technologies have transformed this process by:

- Analyzing genomic data: AI identifies genetic markers that are important for plant traits.
- Predicting trait performance: AI algorithms can forecast the outcome of specific

genetic combinations, speeding up the breeding process.

- Exploring genetic diversity: AI tools facilitate the identification of novel traits and the development of crop varieties adapted to diverse agroecological conditions [6].

As a result, AI accelerates the development of crops with superior yield, resilience, and nutritional quality, reducing the time and resources needed for traditional breeding techniques. 5. AI in Disease Detection and Ecosystem Monitoring.

Beyond crop management and breeding, AI is revolutionizing disease detection, ecosystem monitoring, and biodiversity conservation. AI applications in these areas include:

- Early disease detection: AI uses image recognition and spectral analysis to detect plant diseases at early stages, allowing for prompt intervention.
- Species distribution modeling: AI predicts shifts in species distributions in response to environmental changes, aiding in biodiversity conservation.
- Ecosystem management: AI helps in modeling ecological systems and understanding their dynamics to ensure the sustainable management of natural resources.

By embracing AI as a catalyst for change, researchers, farmers, and policymakers can harness its transformative potential to address pressing challenges such as climate change, food security, and biodiversity conservation. This collaboration between AI and plant science holds the promise of shaping a more equitable, resilient, and sustainable future for plant life and humanity alike.

2. THE MARRIAGE OF AI AND PLANT SCIENCE

The marriage of AI and plant science signifies a pivotal moment in agricultural innovation, heralding a new era of precision, efficiency, and sustainability. AI's intrinsic ability to process vast datasets, discern intricate patterns, and forecast outcomes aligns seamlessly with the multifaceted intricacies of plant biology. By amalgamating machine learning algorithms, robotics, remote sensing technologies, and big data analytics, researchers are endowed with unprecedented

capabilities to unravel the complexities of plant behavior, decipher ecosystem dynamics, and optimize agricultural practices [7].

Unveiling plant growth insights through AI: At the heart of this convergence lies the promise of unlocking invaluable insights into the fundamental processes governing plant growth, development, and response to environmental stimuli. AI-driven models can discern subtle correlations between genetic traits, environmental variables, and agronomic practices, shedding light on the intricate interplay shaping crop performance. Whether it's deciphering the genetic basis of drought tolerance, predicting optimal planting dates based on climate forecasts, or optimizing nutrient management strategies for enhanced yield, AI empowers researchers to navigate the complexities of plant science with newfound precision and efficacy.

AI's role in revolutionizing field-based research: Moreover, the integration of AI with robotics and remote sensing technologies revolutionizes field-based research and monitoring. Autonomous drones equipped with advanced sensors can survey vast expanses of agricultural land, capturing high-resolution imagery and multispectral data for real-time analysis [8]. These data streams, when fed into AI algorithms, enable rapid assessment of crop health, detection of pest infestations, and identification of nutrient deficiencies. By leveraging robotic platforms for precision application of inputs, such as targeted spraying or soil amendments, farmers can optimize resource utilization, minimize environmental impact, and maximize productivity.

AI's potential in advancing ecological understanding: Furthermore, AI holds immense potential in advancing our understanding of complex ecological interactions and facilitating ecosystem-based approaches to agriculture [9]. By analyzing vast repositories of ecological data, AI algorithms can model species interactions, predict the spread of invasive pests, and assess the impact of land-use changes on biodiversity. These insights not only inform sustainable land management practices but also enable the development of resilient agricultural systems capable of adapting to shifting environmental conditions and mitigating the effects of climate change.

A paradigm shift in agricultural research: In essence, the convergence of AI and plant

science transcends disciplinary boundaries, catalyzing a paradigm shift in agricultural research, innovation, and practice. As we navigate the challenges of feeding a growing global population amidst mounting environmental pressures, the role of AI as a transformative tool for enhancing agricultural sustainability and resilience becomes increasingly indispensable [10]. By harnessing the synergies between AI's analytical prowess and the intricate complexities of plant biology, we embark on a journey towards a more prosperous, equitable, and sustainable future for agriculture and society at large.

3. PRECISION AGRICULTURE

Precision agriculture represents a revolutionary approach to farming, driven by the integration of AI technologies such as machine learning algorithms and computer vision. This innovative paradigm uses advanced data analytics to enhance productivity, improve resource efficiency, and promote environmental sustainability. By leveraging the analytical power of AI, farmers can extract valuable insights from a variety of data sources, including sensors, satellites, and drones, enabling data-driven decisions tailored to the specific needs of crops and fields [11].

Targeted interventions in crop management: Central to precision agriculture is the concept of targeted interventions, where AI algorithms analyze real-time data to optimize various aspects of crop management. For example, AI can analyze soil moisture levels, weather conditions, and crop health to recommend precise irrigation schedules. This ensures crops receive the optimal amount of water, reducing waste. Similarly, AI can assess soil nutrient levels and suggest customized fertilization strategies, improving nutrient uptake by plants while preventing the over-application of fertilizers, which can harm the environment and degrade soil [12].

AI-Powered pest and disease management: AI technologies also play a key role in proactive pest and disease management. Through image recognition and pattern analysis, AI systems can detect early signs of pest infestations or disease outbreaks. Drones equipped with high-resolution cameras or sensors allow farmers to monitor their fields with great detail, identifying problem areas before pests or diseases cause significant damage (Aleksandrov 2022). This targeted approach reduces the need for broad-spectrum

pesticides, minimizes the risk of resistance development, and promotes ecological balance by preserving biodiversity.

3Optimizing machinery operations with AI: Beyond crop management, AI can optimize farm machinery operations to minimize fuel consumption and reduce greenhouse gas emissions. By integrating AI algorithms into equipment like tractors and harvesters, farmers can improve route planning, adjust seeding rates, and fine-tune machinery settings in real-time based on varying field conditions. This not only boosts operational efficiency but also cuts input costs and lowers the environmental impact of farming, contributing to a more sustainable agricultural system [13].

The future of sustainable farming: Overall, the incorporation of AI in precision agriculture marks a significant leap toward transforming traditional farming into data-driven, sustainable systems. AI enables farmers to make informed decisions by analyzing vast datasets and providing actionable insights, leading to optimized resource use, minimized environmental harm, and improved long-term agricultural productivity [14]. As global population growth and environmental pressures intensify, precision agriculture offers a vital pathway to meeting rising food demands while preserving natural resources for future generations.

4. CROP MONITORING AND DISEASE DETECTION

Introduction to AI in Crop Monitoring and Disease Detection Crop monitoring and disease detection are essential aspects of modern agriculture, where AI plays a transformative role. Through advanced computer vision algorithms, AI facilitates the early identification of diseases and pests, allowing farmers to intervene promptly and minimize potential crop damage [14]. This proactive strategy not only helps preserve crop health but also encourages sustainable farming by reducing the dependency on chemical pesticides and limiting environmental harm.

Traditional vs. AI-driven approaches: Conventional methods of detecting diseases and pests often rely on manual inspection or periodic scouting, which can be labor-intensive, time-consuming, and susceptible to human error. AI-driven systems, on the other hand, utilize computer vision technology to analyze images of crops collected via drones, satellites, or field-

based sensors. These algorithms can detect early-stage signs of disease, nutrient deficiencies, or pest infestations—such as leaf discoloration, lesions, or irregular growth patterns—with high precision. By rapidly processing large volumes of image data, AI enables early detection, empowering farmers to take timely actions that prevent further spread and damage.

Targeted and effective interventions: With AI's ability to pinpoint the underlying causes of plant symptoms, farmers can implement precise control measures tailored to the specific issue. Whether using biological controls, resistant plant varieties, or cultural practices, AI helps farmers manage crop health more effectively and sustainably [15]. This targeted approach significantly reduces the need for broad-spectrum pesticides, which can negatively impact beneficial organisms, degrade soil health, and disrupt ecosystem balance.

Scalability and efficiency in field monitoring: AI-driven crop monitoring systems also bring scalability and efficiency to the forefront. They allow for the continuous surveillance of large agricultural areas with unmatched speed and accuracy [16]. By integrating AI algorithms into automated platforms such as autonomous drones or smart cameras, farmers can routinely survey their fields and detect emerging issues before they become widespread problems. This constant monitoring not only mitigates the risk of significant crop losses but also ensures that interventions are strategically targeted where they are needed most, improving resource efficiency.

AI's role in sustainable farming: The adoption of AI in crop monitoring and disease detection marks a major leap forward in agricultural technology, providing farmers with advanced tools to boost productivity, promote sustainability, and increase crop resilience. By enabling the early detection of pests and diseases, AI helps farmers make informed decisions, minimize crop damage, and reduce their dependence on chemical treatments [17].

As the agricultural sector grapples with the challenge of feeding a growing global population while conserving natural resources, AI-driven innovations offer a promising path toward a more resilient and environmentally friendly food production system,

5. GENOMIC RESEARCH AND CROP IMPROVEMENT

Genomic research lies at the forefront of plant science, offering insights into the genetic blueprints underlying various traits essential for crop improvement and agricultural sustainability. With the advent of high-throughput sequencing technologies, vast genomic datasets have become available, providing researchers with unprecedented opportunities to unravel the complexities of plant genomes [18]. However, the sheer volume and complexity of genomic data present significant challenges in analysis and interpretation. This is where AI emerges as a transformative tool, accelerating genomic research and facilitating crop improvement through efficient data analysis and predictive modeling.

Machine learning algorithms, a subset of AI techniques, excel in analyzing large-scale genomic datasets, identifying patterns, and making predictions based on underlying genetic mechanisms [19]. By training these algorithms on diverse genomic data, researchers can decipher the function of genes, unravel gene regulatory networks, and predict the phenotypic outcomes of genetic variations. This enables scientists to prioritize candidate genes associated with desirable traits for further investigation and validation, expediting the process of crop improvement. Moreover, AI-driven approaches enhance the efficiency of traditional breeding methods by guiding the selection of parental lines and accelerating the generation of improved crop varieties.

By leveraging machine learning algorithms to analyze genotype-phenotype relationships, researchers can predict the performance of different genetic combinations and identify promising candidates for breeding programs [20]. This targeted approach minimizes the need for labor-intensive field trials and enables breeders to focus their efforts on developing cultivars with enhanced resilience, improved nutritional content, and greater resistance to biotic and abiotic stressors. By correlating genomic data with phenotypic data collected from field trials or controlled experiments, machine learning algorithms can pinpoint genomic regions linked to target traits, such as yield, quality, or stress tolerance. This enables breeders to employ marker-assisted selection techniques to efficiently introgress desirable traits into elite germplasm, accelerating the development of

improved crop varieties tailored to the needs of farmers and consumers [21]. By analyzing genomics data from diverse plant populations, researchers can identify genetic variants associated with traits such as drought tolerance, disease resistance, and nutritional quality [22]. This knowledge not only informs breeding efforts but also provides insights into the evolutionary processes shaping plant diversity and adaptation, with implications for conservation and ecosystem management.

In summary, AI is revolutionizing genomic research in plant science, enabling scientists to unlock the full potential of genetic diversity for crop improvement and agricultural innovation. By accelerating the analysis of genomic datasets, predicting gene functions, and guiding breeding strategies, AI empowers researchers to develop crops with enhanced resilience, nutritional content, and productivity [23]. As the global population continues to grow and environmental challenges escalate, AI-driven approaches offer promising solutions for creating a more sustainable and food-secure future.

6. CHALLENGES CLIMATE CHANGE

It presents significant challenges to agriculture, with shifting weather patterns, extreme events, and rising temperatures jeopardizing global food security. Developing climate models that accurately predict the impacts of these changing conditions on crops is crucial for informing adaptation strategies and enhancing the resilience of agricultural systems [24].

The role of AI: In this context, artificial intelligence (AI) emerges as a powerful ally, utilizing advanced data analytics and predictive modeling techniques to improve the accuracy and reliability of climate projections. This, in turn, facilitates adaptive decision-making for farmers facing the uncertainties associated with climate change.

Limitations of traditional models: Traditional climate models often rely on complex mathematical equations to simulate interactions among various components of the Earth's climate system, including the atmosphere, oceans, land surface, and biosphere. While they provide valuable insights into long-term climate trends, these models frequently struggle to capture intricate feedback mechanisms and localized effects that directly influence agricultural productivity at regional scales.

Advantages of AI-driven approaches: AI-driven methods offer significant advantages by augmenting traditional climate models with machine learning algorithms that can extract patterns and correlations from extensive datasets [25]. By analyzing historical climate data, satellite imagery, and real-time sensor data, AI systems can identify trends, detect anomalies, and forecast future climate scenarios with greater resolution and accuracy.

Simulation of climate impacts: AI-enhanced climate models empower researchers to simulate the impacts of climate change on crucial agricultural variables such as crop growth, water availability, and pest dynamics. By incorporating feedback mechanisms between climate and agricultural systems, these models provide actionable insights for farmers, policymakers, and agricultural stakeholders to adapt their practices and mitigate adverse climate effects [26].

Development of decision support systems: AI also facilitates the creation of decision support systems that convert climate projections into practical recommendations for farmers. By integrating climate data with agronomic knowledge, soil information, and crop models, AI-powered tools can generate personalized adaptation strategies tailored to specific crops, regions, and farming systems.

Real-time monitoring and adaptive management: Moreover, AI enables real-time monitoring of climate and crop conditions, allowing farmers to make adaptive management decisions in response to changing environmental cues. By deploying sensors, drones, and satellite imagery equipped with AI algorithms, farmers can track soil moisture levels, crop health indicators, and weather forecasts with unprecedented granularity.

Proactive interventions: This real-time data feedback loop facilitates proactive interventions, such as adjusting irrigation schedules, implementing drought-tolerant crop varieties, or deploying early warning systems for pest outbreaks. These measures help minimize yield losses and optimize productivity under variable climatic conditions.

In summary, AI-driven climate modeling and adaptation offer immense potential for enhancing the resilience and sustainability of agricultural systems in the face of climate change. By

leveraging advanced data analytics and predictive modeling techniques, AI equips researchers and farmers to anticipate and respond to the complex challenges posed by evolving climatic patterns. As global climate conditions continue to shift, AI-driven approaches serve as invaluable tools for ensuring food security, environmental sustainability, and livelihood resilience in agricultural communities worldwide [27].

7. RESOURCE OPTIMIZATION

Importance of resource optimization: In the context of modern agriculture, resource optimization has become increasingly crucial due to escalating resource constraints and environmental challenges. To address these issues, AI-driven optimization tools have emerged as innovative solutions that empower farmers to manage resources more efficiently and sustainably.

Leveraging data for informed decisions: By utilizing advanced data analytics and predictive modeling techniques, these AI tools enable farmers to make well-informed decisions regarding resource allocation. This ensures that water, fertilizers, energy, and other inputs are used judiciously while simultaneously maximizing productivity and profitability.

Optimizing planting and crop management: One significant area where AI-driven optimization tools shine is in predicting optimal planting times and effective crop management practices. By analyzing historical climate data, soil conditions, and crop growth models, these tools can provide personalized recommendations tailored to individual farms. Factors such as weather patterns, market demand, and agronomic considerations are all taken into account, allowing farmers to plant crops at the most advantageous times and employ appropriate management techniques.

Enhancing irrigation management: AI-powered irrigation management systems are essential for optimizing water use, particularly in areas that face water scarcity or drought conditions [28]. By integrating sensor data, weather forecasts, and real-time soil moisture monitoring, these systems can dynamically adjust irrigation schedules. This ensures that water is delivered precisely when and where it is needed, promoting optimal crop growth while

conserving vital water resources and minimizing environmental degradation.

Optimizing fertilizer use: Similarly, AI-driven nutrient management tools provide farmers with valuable insights into optimizing fertilizer application. These tools analyze soil nutrient levels, crop nutrient uptake rates, and fertilizer efficiency data to recommend precise fertilization strategies tailored to specific crops and soil types. By minimizing excess nutrient applications, farmers can improve nutrient use efficiency, reduce input costs, and lower the risk of nutrient runoff into water bodies, thereby enhancing environmental sustainability and protecting water quality [29].

Energy management on farms: In addition to water and nutrient management, AI-driven energy management systems play a vital role in optimizing energy use across agricultural operations. These systems analyze energy consumption patterns, weather data, and equipment performance metrics to identify opportunities for enhancing energy efficiency and reducing costs. Implementing strategies such as upgrading to energy-efficient equipment, optimizing machinery scheduling, and integrating renewable energy sources allows farmers to lower energy expenses, decrease carbon emissions, and improve overall farm sustainability.

AI-driven optimization tools are transforming resource management in agriculture, enabling farmers to make data-driven decisions that enhance resource efficiency, boost productivity, and foster environmental sustainability [30]. By harnessing advanced data analytics and predictive modeling, these tools empower farmers to optimize the use of water, fertilizers, energy, and other inputs, leading to increased cost-effectiveness and profitability. As the agricultural sector grapples with challenges related to resource scarcity, climate change, and environmental degradation, AI-driven optimization tools offer essential solutions for developing resilient and sustainable farming systems for the future.

8. CHALLENGES AND ETHICAL CONSIDERATIONS

The integration of AI in plant science holds immense potential to revolutionize agriculture and address pressing challenges such as food security, environmental sustainability, and climate resilience. However, this transformative

technology also presents a range of challenges and ethical considerations that must be carefully addressed to ensure its responsible and equitable deployment in agricultural systems [31].

8.1 Data Privacy and Security

One of the foremost challenges is data privacy and security. AI-driven systems rely on vast amounts of data, including sensitive information about crops, soils, and farming practices. Ensuring the privacy and security of this data is crucial to prevent unauthorized access, misuse, or exploitation. Farmers, researchers, and agricultural stakeholders must implement robust data protection measures, such as encryption, access controls, and anonymization techniques, to safeguard sensitive information and preserve data integrity.

8.2 Algorithmic Bias and Discrimination

Another challenge is the potential for algorithmic bias and discrimination. AI algorithms learn from historical data, which may reflect biases or inequalities present in society. If not carefully monitored and mitigated, these biases can perpetuate inequities in agricultural decision-making, resource allocation, and access to opportunities. It is essential to conduct regular audits of AI algorithms, assess their fairness and transparency, and implement measures to mitigate bias. This includes utilizing diverse training data, ensuring algorithmic transparency, and adhering to fairness-aware design principles [32].

8.3 Equitable Access to Technology

Furthermore, ensuring equitable access to AI technologies and capabilities is critical to prevent the exacerbation of existing disparities in agriculture. Smallholder farmers, marginalized communities, and resource-constrained regions may lack access to the necessary infrastructure, resources, and technical expertise required to adopt and benefit from AI-driven solutions. Efforts must be made to bridge the digital divide, promote technology transfer, and provide training and support to ensure that all farmers have equal opportunities to harness the potential of AI for improving agricultural productivity and livelihoods.

8.4 Intellectual Property Rights and Data Ownership

Ethical considerations also arise in the context of intellectual property rights and data ownership.

As AI technologies generate valuable insights and innovations, questions arise about who owns the data generated by AI systems, who benefits from its use, and who bears responsibility for any unintended consequences. Transparent and equitable frameworks for data sharing, intellectual property rights, and technology transfer are essential to ensure that the benefits of AI in agriculture are fairly distributed and contribute to the collective good.

Ethical implications of AI-driven decision-making: Moreover, the ethical implications of AI-driven decision-making in agriculture must be carefully considered. As AI algorithms increasingly automate critical decisions related to crop management, resource allocation, and sustainability practices, questions arise about accountability, transparency, and the potential for unintended consequences. Farmers, policymakers, and stakeholders must work collaboratively to develop ethical guidelines, regulatory frameworks, and governance mechanisms to ensure that AI-driven decisions align with societal values, environmental sustainability, and the well-being of farming communities [33].

By addressing issues such as data privacy, algorithmic bias, access to technology, and ethical decision-making, stakeholders can harness the full potential of AI in agriculture while ensuring that its benefits are equitably distributed and aligned with broader societal goals of sustainability, equity, and social justice.

9. CONCLUSION

In conclusion, the fusion of AI and plant science marks a transformative moment in agriculture, presenting unique opportunities to tackle the complex challenges of modern food production. By integrating advanced technologies with scientific insights, AI is reshaping various aspects of plant science, including precision farming, crop monitoring, and genetic research. This collaboration enables farmers to optimize resource use and enhance productivity through data-driven decisionmaking, while also facilitating the rapid analysis of genomic data to develop resilient crops with improved nutritional content and stress resistance. As research advances, the synergy between AI and plant science promises to deliver innovative solutions for sustainable agriculture, addressing global issues like climate change and food security. Ultimately, this partnership holds significant potential to create a more resilient, efficient, and sustainable food

system, benefiting both agriculture and humanity as a whole.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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