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Integrating Bioactive Compounds and Artificial Intelligence for Sustainable Horticulture: A Comprehensive Review

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Abstract

Modern horticulture is experiencing a significant transformation driven by the integration of bioactive compounds and artificial intelligence (AI) technologies. Bioactive compounds—such as plant growth regulators, secondary metabolites, biostimulants, and natural elicitors—play an essential role in improving crop productivity, quality, stress tolerance, and sustainability. At the same time, artificial intelligence tools, including machine learning, deep learning, computer vision, and decision-support systems, are reshaping crop management, disease detection, yield prediction, and precision farming. This review critically explores the combined role of bioactive compounds and AI-based tools in enhancing modern horticulture. We examine the types, mechanisms, and applications of bioactive compounds in horticultural crops, followed by an overview of AI technologies and their application across horticultural production systems. The integration of AI with bioactive compound management is presented as a promising pathway toward data-driven, sustainable, and climate-resilient horticulture. Challenges, ethical considerations, and future prospects are also discussed to support researchers, practitioners, and policymakers.

Keywords: *Bioactive compounds, artificial intelligence, horticulture, plant growth.*

1. Introduction

Horticulture plays a vital role in global food security, nutrition, human health, and economic development, particularly through the production of fruits, vegetables, ornamental plants, and medicinal crops. As consumer demand for high-quality, safe, and nutritionally rich horticultural produce continues to increase, the sector faces growing challenges related to climate change, resource scarcity, environmental degradation, and labor shortages [1]. Conventional horticultural practices that rely heavily on synthetic fertilizers and pesticides are becoming increasingly unsustainable due to their negative impacts on ecosystems, soil health, biodiversity, and human well-being. Therefore, there is an urgent need for innovative and environmentally responsible approaches that enhance productivity while reducing ecological footprints. Bioactive compounds have emerged as promising tools for advancing sustainable horticulture.

These compounds, including plant growth regulators, biostimulants, secondary metabolites, and elicitors, significantly influence plant physiological and biochemical processes even at low concentrations [2]. They improve nutrient use efficiency, stimulate plant growth and development, enhance yield and quality, and strengthen tolerance to both abiotic and biotic stresses. Unlike conventional agrochemicals, many bioactive compounds function by modulating endogenous signaling pathways and metabolic processes, making them particularly valuable for enhancing crop resilience under changing environmental conditions.

Parallel to these advancements in plant-based inputs, digital technologies—especially artificial intelligence (AI)—are transforming modern agricultural systems. Artificial intelligence includes a range of computational approaches such as machine learning, deep learning, computer vision, and data-driven decision-support systems, which enable the analysis of complex and large-scale datasets. In horticulture, AI tools support precision farming by improving crop monitoring, disease detection, yield prediction, irrigation management, and post-harvest handling. These technologies allow growers to make timely, accurate, and site-specific decisions, thereby reducing resource wastage and optimizing input use. The integration of bioactive compounds with artificial intelligence tools represents a powerful and emerging paradigm in modern horticulture. AI-driven systems can detect crop stress at early stages, predict plant responses, and guide the precise application of bioactive compounds tailored to specific crop requirements and environmental conditions [3]. This synergy enhances the effectiveness of bioactive substances while minimizing excessive use, thus supporting sustainability goals. Furthermore, AI-based data analytics facilitate the development and optimization of bioactive formulations by identifying patterns in plant responses across diverse environments. Therefore, this review aims to critically examine the role of bioactive compounds in horticulture, explore key artificial intelligence tools and their applications, and highlight the synergistic integration of these approaches in advancing modern horticultural practices. It also discusses future prospects, challenges, and research directions for achieving a sustainable transformation of horticulture through bioactive compounds and AI-driven technologies. A comprehensive understanding of the interaction between these two domains is essential for developing climate-resilient, resource-efficient, and high-value horticultural systems [4].

2. Bioactive Compounds in Modern Horticulture

Bioactive compounds are increasingly recognized as essential components of sustainable horticultural production systems due to their ability to regulate plant physiological and biochemical processes at low concentrations. These compounds influence plant growth, development, and stress responses by interacting with hormonal pathways, metabolic networks, and gene expression mechanisms. Unlike conventional fertilizers that primarily supply nutrients, bioactive compounds function as regulators and enhancers of plant performance, enabling crops to achieve higher productivity and quality with reduced dependence on synthetic agrochemicals. Their use aligns with global efforts to promote environmentally responsible and climate-resilient agricultural practices.

Among bioactive compounds, plant growth regulators play a central role in shaping horticultural crop development [5]. Auxins, cytokinins, gibberellins, abscisic acid, ethylene, and brassinosteroids collectively regulate key physiological processes such as cell division, elongation, flowering, fruit set, ripening, and senescence. The strategic application of these regulators has been widely adopted to improve crop uniformity, enhance yield, and increase marketable quality in fruits, vegetables, and ornamental plants. By fine-tuning endogenous hormone balance, plant growth regulators help optimize plant responses throughout different stages of growth.

Secondary metabolites represent another important class of bioactive compounds with significant implications for horticulture. These naturally occurring compounds, including phenolics, flavonoids, alkaloids, and terpenoids, contribute to plant defense mechanisms, stress tolerance, and sensory attributes such as color, flavor, and aroma. In horticultural crops, secondary metabolites enhance resistance to pests and diseases while simultaneously improving nutritional and functional qualities valued by consumers [6]. Their antioxidant properties also play a crucial role in protecting plant tissues from oxidative damage, particularly under stress conditions.

Plant biostimulants have gained considerable attention as sustainable inputs that enhance plant performance by stimulating natural physiological processes. Derived from sources such as seaweed extracts, humic substances, amino acids, and beneficial microorganisms, biostimulants improve nutrient uptake efficiency, promote root development, and increase tolerance to abiotic stresses such as drought, salinity, and temperature extremes. Their application not only enhances crop vigor and yield but also contributes to improved soil health and microbial activity, making them highly suitable for integrated and organic horticultural systems.

Elicitors further strengthen plant defense by activating innate immune responses without directly targeting pathogens. Compounds such as salicylic acid, jasmonic acid, chitosan, and microbially derived molecules trigger systemic resistance, enabling plants to respond more effectively to biotic stresses [7]. The use of elicitors reduces dependence on chemical pesticides and supports environmentally friendly pest and disease management strategies. Collectively, bioactive compounds play a multifaceted role in enhancing horticultural productivity, quality, and resilience while supporting sustainable production systems.

3. Artificial Intelligence Tools in Horticultural Systems

Artificial intelligence has emerged as a transformative force in modern horticulture by enabling data-driven decision-making and precision management of crops. AI technologies are capable of processing large and complex datasets generated from sensors, imaging platforms, weather stations, and farm management systems. Through pattern recognition, predictive modeling, and automated decision-support systems, AI tools help optimize horticultural practices while reducing resource use and production risks [8]. These technologies are particularly valuable in high-value horticultural systems, where precision and efficiency are essential. Machine learning algorithms have been widely applied to model crop growth, predict yields, and evaluate the impact of environmental factors on plant performance. By learning from historical and real-time data, machine learning systems can forecast disease outbreaks, nutrient deficiencies, and stress conditions before visible symptoms appear. This predictive capability allows for timely intervention and improved crop management.

Deep learning models, particularly convolutional neural networks, have demonstrated high accuracy in image-based applications such as plant disease detection, pest identification, fruit counting, and maturity assessment. These capabilities enable rapid, non-destructive monitoring of crops across large production areas [9]. Computer vision technologies further enhance horticultural management by enabling automated analysis of visual plant traits. Cameras mounted on drones, robotic systems, or stationary platforms capture high-resolution images that are analyzed to assess plant health, canopy structure, fruit quality, and yield potential. In post-harvest operations, computer vision systems are widely used for sorting and grading fruits and vegetables based on size, color, shape, and surface defects, ensuring consistent quality and reducing post-harvest losses. AI-driven decision-support systems integrate agronomic, climatic, and operational data to provide real-time recommendations for irrigation scheduling, nutrient management, and pest control. These systems enable growers to apply inputs at optimal times and locations, improving resource use efficiency and minimizing environmental impacts.

In protected cultivation systems such as greenhouses and vertical farms, AI algorithms dynamically regulate environmental parameters including temperature, humidity, light, and carbon dioxide levels to maintain optimal growing conditions. This results in increased yields and improved crop quality. Robotics and automation represent another important application of artificial intelligence in horticulture. AI-powered robots are increasingly used for planting, pruning, harvesting, and targeted spraying operations. These systems reduce labor dependency, enhance operational precision, and enable continuous monitoring and timely intervention. As AI technologies continue to evolve, their integration into horticultural systems is expected to play a central role in improving productivity, sustainability, and resilience in response to global agricultural challenges.

4. Synergistic Integration of Bioactive Compounds and Artificial Intelligence

The integration of bioactive compounds with artificial intelligence tools represents a significant advancement in modern horticultural practices, enabling a transition from generalized input application to precision-based crop management. Artificial intelligence systems can analyze real-time data related to plant growth, environmental conditions, and stress indicators, allowing for the targeted and timely application of bioactive compounds [10]. This precision-based approach enhances the effectiveness of bioactive inputs while minimizing waste, environmental contamination, and production costs. By aligning plant physiological needs with data-driven decision-making, this integration supports more efficient and sustainable horticultural systems. AI-based monitoring tools facilitate the early detection of abiotic and biotic stresses through the analysis of plant images, spectral data, and sensor outputs. Once stress symptoms are identified, bioactive compounds such as biostimulants and elicitors can be applied strategically to mitigate adverse effects and strengthen plant defense mechanisms. This proactive management approach improves crop resilience, reduces dependence on chemical pesticides, and enhances overall plant health. The combination of early stress detection and targeted intervention is particularly valuable in high-value horticultural crops, where yield losses can have significant economic implications.

Artificial intelligence algorithms also enable the dynamic regulation of microclimatic factors such as temperature, humidity, light intensity, and carbon dioxide levels, while coordinating the application of growth regulators and biostimulants. This synchronized management creates optimal growth conditions, resulting in increased productivity, improved uniformity, and enhanced product quality. AI-driven systems support continuous optimization by learning from plant responses over time, thereby improving system efficiency and adaptability [11]. Furthermore, artificial intelligence plays a crucial role in accelerating the development and optimization of bioactive compound formulations. By analyzing large datasets generated from field trials and laboratory experiments, AI tools can identify patterns in plant responses and predict the effectiveness of specific compounds or their combinations. This data-driven approach reduces the time and cost associated with product development and supports the creation of customized bioactive solutions tailored to specific crops, environments, and production systems.

5. Challenges, Limitations, and Ethical Considerations

The widespread adoption of bioactive compounds and artificial intelligence tools in horticulture faces several challenges. One major limitation is the variability in plant responses to bioactive compounds under different environmental conditions, crop species, and application methods. Such inconsistencies can reduce grower confidence and highlight the need for standardized application protocols, rigorous field validation, and region-specific recommendations. Additionally, the complex modes of action of many bioactive compounds are not yet fully understood, which limits their optimized use [12].

The implementation of artificial intelligence technologies in horticulture also presents technical and economic challenges. High initial investment costs, limited access to digital infrastructure, and the requirement for technical expertise can restrict adoption, particularly among smallholder and resource-limited growers. Data quality and availability are critical for AI performance, and inaccurate or incomplete datasets may lead to unreliable recommendations. Furthermore, interoperability issues between different digital platforms and hardware systems can hinder seamless integration. Ethical considerations related to data ownership, privacy, and transparency must also be addressed as AI-driven systems become more widespread. The collection and use of farm data raise concerns regarding ownership, usage rights, and the extent of grower control over their information. In addition, increasing reliance on automated decision-making systems may reduce human oversight, emphasizing the need for clear accountability frameworks and ethical guidelines to ensure responsible AI use in horticulture. While bioactive compounds are generally considered safer than conventional agrochemicals, their large-scale production and application must still be evaluated for sustainability and long-term ecological impacts. Regulatory frameworks governing the approval and use of bioactive products vary across regions, creating uncertainty and potential barriers to commercialization. Addressing these challenges requires coordinated efforts among researchers, industry stakeholders, policymakers, and growers to establish clear standards, guidelines, and best practices.

6. Future Perspectives and Research Directions

The future of modern horticulture lies in the continued integration of bioactive compounds and artificial intelligence technologies to develop resilient, efficient, and sustainable production systems. Advances in molecular biology, omics technologies, and plant phenotyping are expected to improve understanding of the mechanisms underlying bioactive compound activity, enabling more precise and effective applications. When combined with AI-driven analytics, these insights will support the development of next-generation bioactive products tailored to specific crops and environmental conditions.

Artificial intelligence technologies are expected to become more accessible, affordable, and user-friendly, facilitating broader adoption across diverse horticultural systems. The integration of AI with Internet of Things (IoT) devices, remote sensing platforms, and autonomous machinery will further enhance real-time monitoring and decision-making capabilities. These advancements will enable predictive and adaptive management strategies that respond dynamically to changing environmental and crop conditions. Long-term field studies are essential to evaluate the combined impacts of bioactive compounds and AI tools on productivity, environmental sustainability, and economic viability. Interdisciplinary collaboration among plant scientists, data scientists, engineers, and social scientists will be crucial for addressing technical, ethical, and socioeconomic challenges. The synergistic application of bioactive compounds and artificial intelligence thus represents a transformative approach to advancing modern horticulture.

7. Conclusion

Bioactive compounds and artificial intelligence tools represent complementary pillars of modern horticulture. Bioactive compounds enhance plant health, productivity, and quality through natural physiological pathways, while AI technologies enable precise, data-driven decision-making across the horticultural value chain. Their integration offers a powerful approach to achieving sustainable, resilient, and high-performing horticultural systems. However, responsible implementation, ethical considerations, and inclusive innovation will be essential to fully realize their potential.

References

1. Pereira, G. C. (2019). Application of biotechnology in producing plant bio-active compounds. In *Natural Bio-active Compounds: Volume 3: Biotechnology, Bioengineering, and Molecular Approaches* (pp. 59-78). Singapore: Springer Singapore.
2. Toscano, S., Trivellini, A., Cocetta, G., Bulgari, R., Francini, A., Romano, D., & Ferrante, A. (2019). Effect of preharvest abiotic stresses on the accumulation of bioactive compounds in horticultural produce. *Frontiers in plant science*, *10*, 1212.
3. Goicoechea, N., &Antolín, M. C. (2017). Increased nutritional value in food crops. *Microbial biotechnology*, *10*(5), 1004-1007.
4. Amodio, C. M., &Colelli, G. (2019). VI International Symposium on Applications of Modelling as an Innovative Technology in the Horticultural Supply Chain Model-IT 2019.
5. Jeschke, P. (2004). The unique role of fluorine in the design of active ingredients for modern crop protection. *ChemBioChem*, *5*(5), 570-589.
6. Manganaris, G. A., Goulas, V., Mellidou, I., &Drogoudi, P. (2018). Antioxidant phytochemicals in fresh produce: exploitation of genotype variation and advancements in analytical protocols. *Frontiers in Chemistry*, *5*, 95.
7. D'Agostino, N., &Tripodi, P. (2017). NGS-based genotyping, high-throughput phenotyping and genome-wide association studies laid the foundations for next-generation breeding in horticultural crops. *Diversity*, *9*(3), 38.
8. Vurro, M., Miguel-Rojas, C., & Pérez-de-Luque, A. (2019). Safe nanotechnologies for increasing the effectiveness of environmentally friendly natural agrochemicals. *Pest management science*, *75*(9), 2403-2412.
9. Morone, P., Koutinas, A., Gathergood, N., Arshadi, M., &Matharu, A. (2019). Food waste: Challenges and opportunities for enhancing the emerging bio-economy. *Journal of cleaner production*, *221*, 10-16.
10. Denisow, B., &Denisow-Pietrzyk, M. (2016). Biological and therapeutic properties of bee pollen: a review. *Journal of the Science of Food and Agriculture*, *96*(13), 4303-4309.
11. Hasan, M. U., Malik, A. U., Ali, S., Imtiaz, A., Munir, A., Amjad, W., & Anwar, R. (2019). Modern drying techniques in fruits and vegetables to overcome postharvest losses: A review. *Journal of Food Processing and Preservation*, *43*(12), e14280.