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AI-driven multi-layer horticulture for climate-resilient farming in Odisha

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Abstract
Horticulture plays a pivotal role in enhancing nutritional security and rural livelihoods in Odisha, India; however, productivity is constrained by climate variability, suboptimal land-use efficiency, and post-harvest losses. Emerging technologies such as artificial intelligence (AI) and Internet of Things (IoT) offer new opportunities for transforming conventional horticulture into a data-driven, climate-resilient system. This mini-review synthesizes recent advances (2024–2026) in AI-enabled precision horticulture and evaluates their integration with multi-layer cropping systems. Multi-layer horticulture improves vertical space utilization by combining perennial, fruit, vegetable, and spice crops within a single production unit, while AI-based systems enable real-time monitoring, predictive irrigation, and adaptive crop management. A conceptual framework tailored to Odisha's agro-climatic conditions is proposed, highlighting potential improvements in resource-use efficiency, yield stability, and economic returns. The integration of AI-driven decision support with multi-layer horticulture is shown to reduce water consumption, enhance productivity, and mitigate climate risks. This review provides a region-specific pathway for sustainable intensification of horticulture in Odisha and identifies future research directions for scalable implementation**.**

Keywords: Artificial intelligence, precision horticulture, multi-layer cropping, climate-resilient agriculture, smart irrigation, Odisha, sustainable farming

Introduction
Horticulture is a rapidly expanding sector of Indian agriculture, contributing significantly to food security, employment generation, and economic development. Odisha, characterized by diverse agro-climatic zones ranging from coastal plains to tribal uplands, possesses considerable potential for the cultivation of fruits, vegetables, spices, and plantation crops. Despite this potential, horticultural productivity in the region remains constrained by several factors, including erratic rainfall patterns, inefficient irrigation practices, fragmented landholdings, and inadequate post-harvest infrastructure.

Climate change has further intensified these challenges by increasing the frequency of droughts, floods, and temperature variability, thereby affecting crop yield and quality. In this context, the adoption of climate-smart agricultural practices is essential for ensuring sustainable horticultural development. Recent advancements in artificial intelligence (AI), machine learning, and Internet of Things (IoT) technologies have enabled the development of precision agriculture systems that facilitate real-time monitoring, predictive analytics, and efficient resource management.

Simultaneously, multi-layer horticulture systems have emerged as an effective strategy for maximizing land-use efficiency and enhancing farm income. By integrating crops of varying heights, growth durations, and resource requirements, these systems optimize vertical space utilization and improve ecological stability. However, the application of AI-driven precision technologies within multi-layer horticulture systems, particularly under Odisha-specific conditions, remains inadequately explored.

Therefore, this mini-review aims to synthesize recent developments in AI-based precision horticulture and evaluate their potential integration with multi-layer cropping systems. The study further proposes a conceptual framework tailored to Odisha, with the objective of enhancing productivity, resource efficiency, and climate resilience in horticultural systems**.**

Multi-Layer Horticulture System
Multi-layer horticulture is an advanced cropping strategy designed to maximize land productivity through the simultaneous cultivation of crops with different canopy heights, rooting patterns, and growth durations within the same field. This system is particularly relevant for regions like Odisha, where landholdings are small and climatic variability affects crop stability. By integrating perennial, seasonal, and short-duration crops, multi-layer horticulture enhances resource-use efficiency, improves farm income, and reduces production risks.

The system utilizes vertical space by arranging crops in layers, ensuring optimal utilization of sunlight, soil nutrients, and water. In Odisha, where diverse agro-climatic zones exist—from coastal humid regions to upland tribal areas—multi-layer horticulture offers a flexible and adaptive approach for sustainable intensification of horticultural production**.**

1. Concept and Scientific Basis
Multi-layer horticulture, also referred to as multi-tier or stratified cropping, is based on ecological principles of complementarity and resource partitioning. Crops with varying canopy architecture and physiological requirements are combined in such a way that competition is minimized while resource utilization is maximized.

The upper canopy captures high-intensity sunlight, while lower layers utilize filtered light. Similarly, deep-rooted crops absorb nutrients from lower soil layers, whereas shallow-rooted crops utilize nutrients from the upper soil

profile. This leads to efficient nutrient cycling and reduced resource wastage.
The system also promotes biodiversity and ecological balance, which contributes to natural pest regulation and improved soil health.

2. Structure of Multi-Layer System for Odisha

The design of a multi-layer system in Odisha depends on crop compatibility, climatic conditions, and market demand. A typical model suitable for Odisha is presented below:

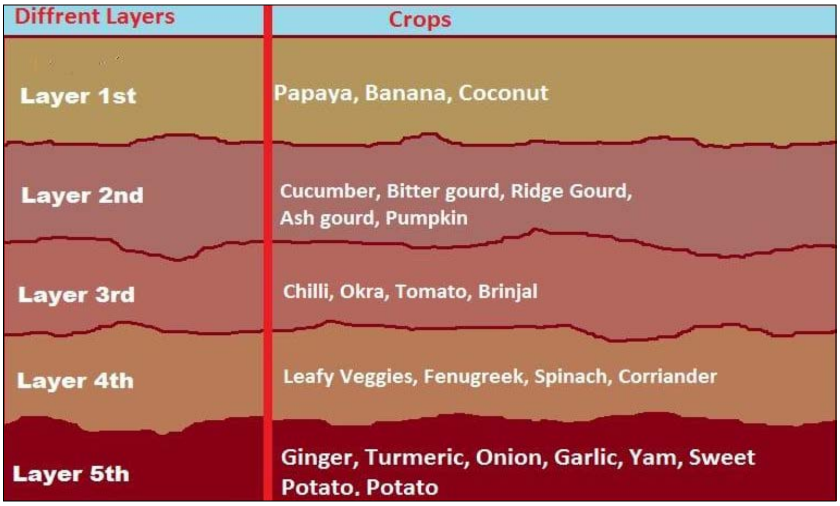

Fig 1: Conceptual diagram of a multi-layer horticulture system suitable for Odisha

Table 1: Odisha-Specific Multi-Layer Cropping Model

Layer	Crop Type	Suitable Crops	Duration	Functional Role
Upper layer	Tree crops	Mango, Coconut, Cashew	Long-term	Shade, microclimate regulation
Middle layer	Fruit crops	Banana, Papaya, Guava	Medium-term	Income stabilization
Lower layer	Vegetables	Tomato, Brinjal, Okra, Chilli	Short-term	Quick economic return
Ground layer	Spices/root crops	Turmeric, Ginger, Colocasia	Seasonal	Soil cover and fertility

This structure ensures continuous production and efficient utilization of available resources throughout the year.

3. Functional Advantages

Efficient Resource Utilization

The multi-layer system optimizes light interception by distributing crops vertically. This improves photosynthetic efficiency and overall productivity per unit area.

Improved Soil Health

Continuous plant cover reduces soil erosion, enhances organic matter content, and supports beneficial microbial activity.

Climate Resilience

The presence of multiple crop layers helps buffer climatic extremes such as high temperature, heavy rainfall, and wind stress. Tree layers reduce evapotranspiration and create a favorable microclimate.

Income Diversification

Farmers benefit from staggered harvesting:
- **Short-term:** vegetables
- **Medium-term:** fruits
- **Long-term:** tree crops

4. Suitability Across Odisha Agro-Climatic Zones

Coastal Plains (Puri, Cuttack, Jagatsinghpur)
- Coconut + Banana + Vegetables
- High humidity supports multi-tier cropping

Central Tableland (Khordha, Nayagarh)
- Mango + Papaya + Vegetables
- Moderate rainfall enables diversified cropping

Tribal/Upland Regions (Koraput, Kandhamal)
- Cashew + Turmeric + Ginger
- Suitable for rainfed and organic systems

5. Limitations and Challenges

Despite its advantages, multi-layer horticulture faces certain constraints:
- High initial establishment cost
- Need for scientific crop planning
- Competition for nutrients if poorly managed
- Limited awareness and technical knowledge among farmers

6. Relevance to Climate-Smart Agriculture

Multi-layer horticulture aligns with climate-smart agriculture principles by enhancing system resilience and reducing environmental impact. It improves carbon sequestration, conserves soil moisture, and reduces dependency on external inputs.
When integrated with modern technologies such as AI-based irrigation and precision farming tools, the system becomes more efficient and adaptable to climate variability, making it highly suitable for sustainable horticulture development in Odisha.

Ai in Precision Horticulture

Artificial intelligence (AI) has emerged as a transformative approach in precision horticulture by enabling real-time monitoring, predictive analytics, and automated decision-making. In recent years, the integration of AI with Internet of Things (IoT)-based sensor networks has significantly improved the efficiency of crop management systems. Soil moisture sensors, temperature probes, and humidity sensors continuously generate field-level data, which are processed using machine learning algorithms to optimize irrigation, fertilization, and crop health monitoring. These technologies are particularly relevant for regions such as Odisha, where variability in rainfall and temperature often leads to inconsistent crop performance [1, 2].

AI-driven irrigation systems utilize predictive models to determine crop water requirements based on real-time environmental conditions and historical datasets. Such systems have been shown to reduce water consumption while maintaining optimal soil moisture levels, thereby improving water-use efficiency in horticultural crops [3, 4]. In multi-layer cropping systems, where crops of different canopy structures and water demands coexist, AI plays a crucial role in balancing resource allocation across layers. By dynamically adjusting irrigation schedules, AI ensures that both deep-rooted and shallow-rooted crops receive adequate moisture without excess loss.

In addition to irrigation management, AI-based image recognition tools have been widely applied for early detection of pests and diseases. Deep learning models can analyze leaf images to identify symptoms at initial stages, enabling timely intervention and reducing dependence on chemical pesticides [5, 6]. Furthermore, AI-assisted yield prediction models help farmers anticipate production levels and make informed decisions regarding harvesting, storage, and marketing [7].

The adoption of AI in horticulture also contributes to improved input efficiency and reduced environmental impact. Precision application of water and nutrients minimizes wastage and enhances sustainability. Studies have demonstrated that AI-integrated systems can increase productivity while lowering operational costs, making them particularly suitable for smallholder farmers [8, 9]. In the context of Odisha, where resource constraints and climate variability pose significant challenges, AI-based precision horticulture offers a viable pathway toward sustainable intensification.

“Therefore, the integration of AI-based precision technologies with multi-layer horticulture systems provides a promising framework for enhancing productivity and sustainability under Odisha conditions.”

Integrated Ai-Driven Multi-Layer Horticulture Model for Odisha

“Unlike conventional horticulture models, the proposed system integrates vertical crop stratification with AI-driven real-time decision support, representing a novel approach for climate-resilient farming in Odisha**.”**

The integration of AI-based precision technologies with multi-layer horticulture systems represents an innovative approach for enhancing productivity and climate resilience in Odisha. This integrated model combines vertical crop stratification with data-driven resource management to optimize overall system performance. The multi-layer structure ensures efficient utilization of sunlight, soil nutrients, and space, while AI technologies provide real-time insights for precise crop management.

In this model, sensor networks are deployed across the field to continuously monitor soil moisture, temperature, humidity, and other environmental parameters. The collected data are transmitted to an AI-based decision support system, where machine learning algorithms analyze patterns and generate recommendations for irrigation and nutrient application. This process enables site-specific management practices, ensuring that each crop layer receives optimal inputs according to its physiological requirements [10, 11].

The working mechanism of the system involves continuous data acquisition, analysis, and automated response. Sensors capture field conditions and transmit data to a central processing unit, where AI models predict irrigation schedules and detect potential stress conditions. Based on these predictions, irrigation systems are activated automatically, minimizing human intervention and reducing resource wastage. In multi-layer systems, this approach is particularly effective in managing the complex interactions between crops of different heights and growth stages.

The integrated model is highly adaptable to the diverse agro-climatic zones of Odisha. In coastal regions, combinations such as coconut, banana, and vegetables can be effectively managed using AI-based irrigation systems. In central regions, mango-based multi-layer systems can benefit from predictive nutrient management. In tribal and upland areas, the integration of spice crops such as turmeric and ginger with tree crops enhances both productivity and soil health. This region-specific adaptability makes the model suitable for large-scale implementation across the state.

Another critical component of the integrated system is post-harvest management. AI tools can assist in predicting optimal harvesting time and storage conditions, thereby reducing post-harvest losses. When combined with improved storage and processing techniques, the system enhances the overall value chain efficiency of horticultural produce [12].

The integration of AI with multi-layer horticulture systems offers several advantages, including increased land-use efficiency, reduced water consumption, improved crop productivity, and enhanced climate resilience. However, challenges such as high initial investment, limited technical knowledge, and infrastructure constraints must be addressed to ensure widespread adoption. Capacity-building programs and government support will play a crucial role in facilitating the transition toward AI-enabled horticulture systems in Odisha.

Overall, the proposed integrated model provides a comprehensive framework for sustainable horticultural development. By combining traditional cropping practices with advanced technologies, it creates a resilient and efficient production system capable of addressing the challenges of climate change and resource scarcity [13, 15].

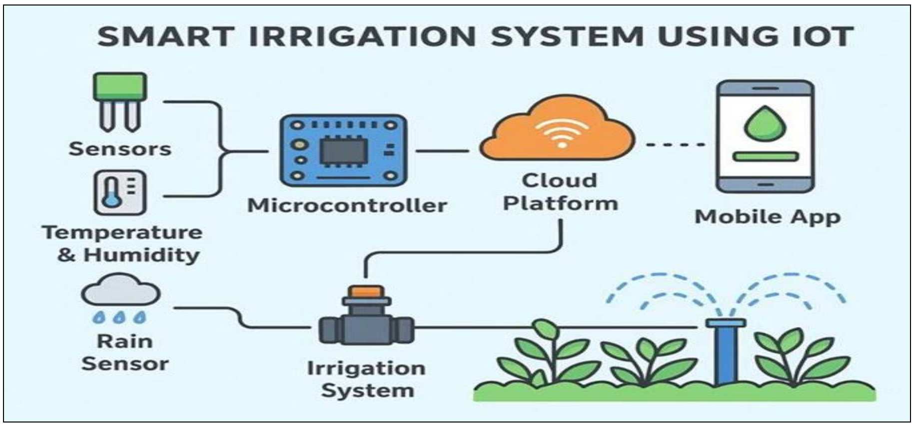

Fig 2: Conceptual framework of an AI-driven multi-layer horticulture system for Odisha

Discussion

The integration of artificial intelligence (AI) with multi-layer horticulture systems represents a coordinated approach for improving productivity and management efficiency under the diverse agro-climatic conditions of Odisha. The structural arrangement of crops across vertical layers enables more efficient utilization of light, water, and soil nutrients, while AI-based decision-support systems provide continuous monitoring and adaptive control of these resources. This interaction between biological design and digital technology creates a responsive production system capable of adjusting to environmental variability [1, 2].

The functioning of multi-layer systems inherently involves complex interactions among crops with different growth habits, rooting depths, and physiological requirements. The incorporation of AI facilitates the management of this complexity by processing real-time data obtained from sensor networks and environmental inputs. Predictive algorithms support synchronization between crop demand and input application, thereby maintaining balanced growth conditions across all layers. Such synchronization is particularly relevant in regions where climatic variability affects crop performance, as it allows the system to respond dynamically to fluctuations in moisture availability and temperature [3, 4].

The integration framework also reflects broader developments in digital agriculture, where data-driven approaches are increasingly applied to optimize production systems. Continuous feedback loops between data collection, analysis, and field-level response enable more precise management compared to conventional practices. This enhances system stability and supports consistent crop performance over time. The combination of vertical crop diversification with AI-enabled control mechanisms thus represents a shift toward more structured and intelligent horticultural systems [5, 7].

Furthermore, the alignment between crop stratification and technological intervention contributes to improved coordination of agronomic practices across different growth stages. AI-based models assist in regulating irrigation and nutrient delivery according to crop-specific needs, ensuring that resource application remains consistent with plant requirements. This integration strengthens the overall coherence of the production system and supports efficient utilization of available inputs [8, 10].

The discussion indicates that the convergence of multi-layer horticulture and AI-based precision technologies forms a unified framework that aligns with current trends in climate-resilient and sustainable agriculture. In the context of Odisha, such an approach provides a scientifically grounded pathway for improving horticultural productivity while maintaining adaptability to environmental variability [11, 15].

Future Perspectives

The future of horticultural systems is increasingly aligned with the advancement of digital agriculture, where artificial intelligence (AI), remote sensing, and data-driven platforms are expected to play a central role in optimizing production processes. In the context of Odisha, the integration of AI with multi-layer horticulture systems can be further strengthened through the adoption of advanced sensing technologies, including satellite-based monitoring and unmanned aerial vehicles (UAVs), which enable large-scale assessment of crop health and environmental conditions [16, 17]. These tools can enhance the precision of decision-making by providing high-resolution spatial and temporal data, thereby improving the responsiveness of horticultural management systems.

The development of cost-effective and user-friendly AI platforms will be essential for ensuring wider adoption among smallholder farmers. Mobile-based applications and cloud-integrated advisory systems can facilitate real-time communication between farmers and decision-support tools, enabling timely interventions based on field conditions. Such digital interfaces can bridge the gap between advanced technologies and practical farm-level implementation, particularly in regions where access to technical expertise is limited [18, 19].

Future research should also focus on refining crop-specific algorithms that consider the interactions among different layers in multi-tier systems. The incorporation of predictive climate models into AI frameworks can improve the capacity of horticultural systems to adapt to weather variability and extreme events. Additionally, integration with smart post-harvest technologies, including automated grading, storage monitoring, and supply chain optimization, can enhance the overall efficiency of horticultural value chains [20, 22].

The convergence of biological and digital systems is expected to redefine horticulture as a knowledge-intensive and technology-driven sector. Continued innovation, supported by institutional collaboration and policy initiatives, will be critical for scaling AI-enabled multi-layer horticulture systems and ensuring their long-term sustainability [23, 25].

Conclusions

The present study demonstrates that the integration of artificial intelligence (AI) with multi-layer horticulture systems provides a scientifically robust framework for enhancing productivity and resource-use efficiency under the diverse agro-climatic conditions of Odisha. The combination of vertical crop stratification with data-driven decision-making enables optimized management of water, nutrients, and environmental factors, resulting in a more adaptive and resilient horticultural production system. The proposed approach reflects a transition from conventional farming practices toward intelligent, precision-based agriculture.

The synthesis of recent developments in AI and multi-layer cropping highlights the potential of such integrated systems to support sustainable intensification of horticulture. By aligning structural crop design with advanced technological interventions, the model facilitates improved coordination of agronomic practices and enhances system stability under variable climatic conditions. This integration is particularly relevant for regions characterized by small landholdings and resource constraints.

Overall, AI-driven multi-layer horticulture systems represent a forward-looking strategy for modernizing horticulture and strengthening climate-resilient farming practices. The adoption of such approaches can contribute to long-term agricultural sustainability while supporting the evolving demands of food production and environmental management [16, 25].

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