Dr. Krishan Kumar Singh is an Associate Professor at the faculty of Agriculture, Guru Kashi University, Talwandi Sabo-151302, Bathinda (Pb.), India. He completed his M.Sc. and Ph.D. in the field of Horticulture from the H.N.B. Garhwal Central University. He received UGC Ph.D. Central University Fellowship from 2011 to 2015. He has published more than 65 research papers and 13 Review papers in National/International Journals and presented papers in many conferences. He also published 22 chapters in different books. He awarded Young Scientist award from National Seminar on Todays Innovations - Tomorrows Sustainability in Allied Sciences, Technology, Management and Education. (25-26 May, 2013). He has vast experience of teaching of under graduate, post graduate programme and research in the field of his specialization.

Dr. Anupam Pratap Singh serves as an Assistant Professor in the Department of Botany at the Constituent Government College, Richha, affiliated with M.J.P. Rohilkhand University, Bareilly, Uttar Pradesh, India. He obtained his M.Sc. and Ph.D. degrees in Botany from M.J.P. Rohilkhand University, Bareilly. Dr. Singh has authored and co-authored more than fifteen research articles published in reputed national and international journals and has presented his findings at numerous scientific forums. He has also contributed eleven chapters to edited academic volumes. His research and teaching interests encompass Angiosperm Taxonomy, Ethnobotany, and Herbal Medicine, with a particular focus on the documentation and scientific validation of traditional plant knowledge.

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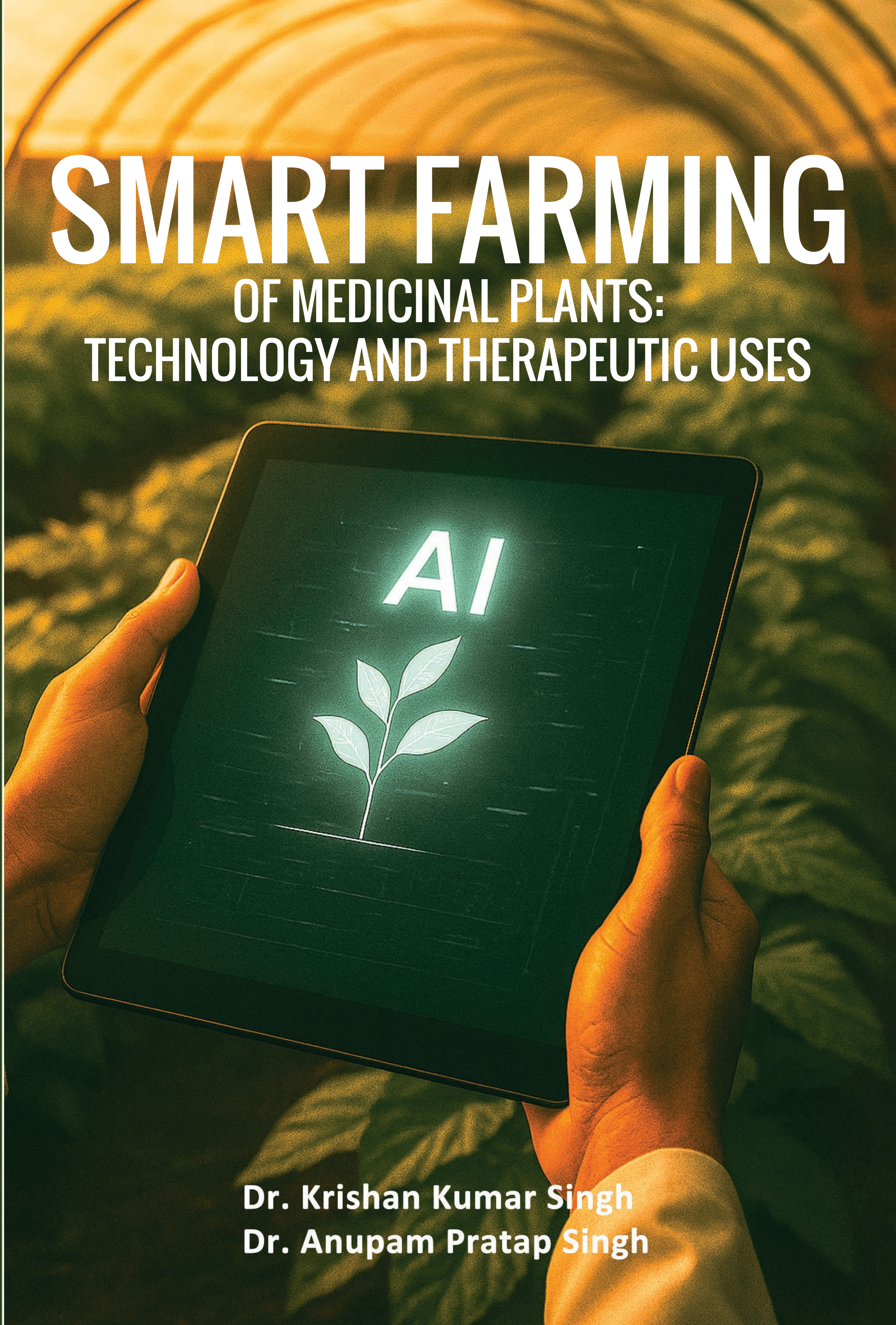

Dr. Krishan Kumar Singh
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Smart Farming of Medicinal Plants: Technology and Therapeutic Uses

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With heartfelt appreciation,
The Editors

PREFACE

The convergence of agriculture, technology, and traditional medicine has opened a new frontier in sustainable cultivation - smart farming of medicinal plants. As global demand for natural remedies, herbal formulations, and plant-derived bioactive compounds continues to rise, integrating modern technological advancements into medicinal plant production has become essential. Smart farming, driven by Artificial Intelligence (AI), the Internet of Things (IoT), remote sensing, and precision agriculture, is transforming traditional cultivation practices into data-driven, efficient, and environmentally sustainable systems. Medicinal plants are a vital resource for the pharmaceutical, nutraceutical, and cosmetic industries. However, inconsistent quality, environmental degradation, and unsustainable harvesting have often threatened their availability and therapeutic efficacy. Smart farming offers practical solutions by ensuring precise control of environmental parameters such as temperature, humidity, soil moisture, and nutrient levels. Through IoT-based sensors, drones, and automated irrigation systems, farmers can monitor real-time plant health, optimize resource use, and increase yield without compromising quality. Moreover, AI-powered predictive models assist in disease detection, pest management, and growth forecasting, enabling informed decision-making and reducing dependency on chemical inputs. The integration of digital tools with biotechnology further enhances the medicinal value of plants. Technologies such as tissue culture, metabolomic profiling, and genetic improvement ensure the conservation of rare and endangered medicinal species while promoting the production of high-value phytochemicals. These approaches not only contribute to biodiversity preservation but also support rural livelihoods by linking farmers with global herbal and pharmaceutical markets.

This book, *Smart Farming of Medicinal Plants: Technology and Therapeutic Uses*, aims to bridge the gap between traditional wisdom and modern innovation. It provides a comprehensive understanding of how digital agriculture, coupled with scientific cultivation techniques, can revolutionize the production and utilization of medicinal plants. The focus extends beyond technology to encompass sustainability, climate resilience, and ethical sourcing - principles that are vital for the future of green healthcare. By exploring interdisciplinary perspectives, this work serves researchers, practitioners, policymakers, and students interested in the intersection of technology, agriculture, and medicine. It highlights that the true potential of medicinal plant cultivation lies not only in harnessing nature's healing power but also in cultivating it intelligently, responsibly, and sustainably for generations to come.

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CHAPTER – 3

AI and IoT Innovations in Smart Greenhouses: Advancing the Cultivation, Quality and Conservation of Ayurvedic Medicinal Species

[1*]Krishan Kumar Singh and [2]Shiv Pratap Singh
[1]Faculty of Agriculture, Guru Kashi University, Talwandi Sabo, Bathinda, 151302 Punjab India
[2]Department of Botany, School of Sciences, IFTM University, Moradabad, 244102, India
*Corresponding Author Email: forekrishna@gmail.com

Abstract

The integration of Internet of Things (IoT) technologies into smart farming offers immense potential for advancing the cultivation and conservation of medicinal and Ayurvedic plants. This review highlights how IoT-based systems enhance growth, yield, and phytochemical quality through precision monitoring and efficient resource management. By enabling real-time data collection, environmental regulation, and predictive analytics, smart greenhouses optimize critical parameters such as temperature, humidity, light, and soil conditions. The paper discusses key components, advantages, challenges, and future prospects of IoT-enabled agriculture, emphasizing its importance in promoting biodiversity conservation and pharmaceutical innovation. Case studies involving Ashwagandha (*Withania somnifera*), Tulasi (*Ocimum tenuiflorum*), Kumari (*Aloe vera*), and Haridra (*Curcuma longa*) demonstrate the tangible benefits of these technologies. Overall, the review underscores IoT's transformative role in connecting traditional medicinal plant wisdom with modern

precision agriculture to ensure sustainable, high-quality, and scientifically managed production systems.

Keywords: Medicinal plant, IA, IoT, Cultivation, Quality, Conservation

1. Introduction

Medicinal plants play a crucial role in global healthcare, underpinning traditional medicine systems and providing key raw materials for modern pharmaceuticals. Worldwide, over 80% of people in developing countries depend on herbal medicines for their primary healthcare needs. Rising global demand for herbal products, however, has intensified pressure on the cultivation, supply, and conservation of these valuable plant species. Unsustainable harvesting, habitat degradation, and the impacts of climate change have further endangered numerous medicinal plants, with several species now classified as vulnerable or at risk of extinction (Chauhan and Sharma, 2025; Sharma *et al*., 2022; Singh *et al*., 2025).

In this context, smart farming leveraging the Internet of Things (IoT) offers a promising approach to overcome the challenges of cultivating and conserving medicinal plants. IoT-enabled systems allow precise monitoring of soil properties, irrigation requirements, plant health, and environmental conditions, ensuring optimal growth and sustainable resource use. Although IoT applications in general agriculture are well-documented, their specific use for Ayurveda-related medicinal plants remains limited. To promote cultivation and conservation, the Government of India, through the Ministry of Ayush, has initiated several programs. The National Ayush Mission (NAM) supports market-oriented cultivation of 140 prioritized medicinal plant species with subsidies ranging from 30% to 75% based on demand. NAM also funds nurseries, postharvest infrastructure, and marketing linkages, bringing over 56,000 hectares under cultivation. Additionally, the National Medicinal Plants Board (NMPB) promotes in situ and ex situ conservation, research, and livelihood support. The upcoming Pradhan Mantri VRIKSH AYUSH Yojana under the ₹4000 crore Atma Nirbhar Bharat initiative seeks to further expand herbal cultivation nationwide (Singh *et al*., 2019).

The Ministry of Ayush, Government of India, places strong emphasis on integrating traditional medicinal knowledge with modern technological innovations. While IoT adoption in agriculture is rapidly expanding, its application in medicinal plant cultivation remains limited. A notable research gap exists, as there is a lack of comprehensive, evidence-based reviews assessing the role of IoT technologies in the cultivation and conservation of Ayurvedic medicinal plants. Additionally, existing studies often overlook the policy-level support provided by initiatives such as Ayush, which actively promote traditional medicine systems in India. The integration of IoT-enabled smart farming can enhance the cultivation of medicinal plants crucial for Ayurveda and other traditional systems, supporting biodiversity conservation and ensuring a consistent supply of high-quality raw materials. Furthermore, the Ministry of Ayush encourages sustainable use of natural resources, aligning with the objectives of IoT-based smart farming. IoT-enabled greenhouse systems create controlled environments, optimizing growth conditions and enhancing the concentration of bioactive phytochemicals critical for therapeutic applications (Atal *et al*., 2025; Singh *et al*., 2025).

2. IoT Technologies in Agriculture

2.1. *Sensors*

Sensors are the foundational components of IoT-based agricultural systems. They are devices that detect and measure various environmental and crop-related parameters and convert them into digital signals that can be analyzed. Sensors provide real-time data essential for monitoring soil conditions, climate variables, and plant health.

- **Soil Sensors:** These sensors monitor soil moisture, temperature, pH, and nutrient levels, which are critical for irrigation scheduling and fertilization. Soil moisture sensors ensure that crops receive the optimal amount of water, preventing over-irrigation and water wastage. Nutrient sensors help maintain soil fertility by detecting deficiencies and guiding the application of fertilizers.
- **Climate Sensors:** These sensors measure environmental parameters such as temperature, humidity, light intensity, rainfall, wind speed, and solar radiation. Data from climate sensors allow farmers to predict weather-related risks, optimize greenhouse conditions, and protect crops from adverse climatic events.
- **Crop Sensors:** These include multispectral, hyperspectral, or optical sensors that monitor plant growth, health, and stress conditions. Crop sensors can detect early signs of disease, pest infestation, or nutrient deficiency, enabling timely interventions that improve yield and quality.
- **Water Quality Sensors:** In areas where irrigation water quality is variable, sensors monitor parameters such as pH, salinity, and dissolved oxygen, ensuring safe and effective irrigation practices.

2.2. *Actuators*

Actuators are devices that perform specific actions in response to data collected from sensors. They are critical for implementing automated farming practices and maintaining optimal growth conditions in real time.

- **Irrigation Actuators:** These systems automatically regulate water supply based on soil moisture data, enabling precision irrigation and conserving water resources. Common examples include drip irrigation controllers and solenoid valves.

- **Fertigation Systems:** Actuators in fertigation setups deliver precise amounts of fertilizers and nutrients directly to crops based on sensor feedback, ensuring optimal nutrient availability and minimizing wastage.
- **Climate Control Systems:** In greenhouses and controlled environments, actuators operate fans, heaters, humidifiers, shading systems, and cooling units to maintain desired temperature, humidity, and light conditions. This helps maximize plant growth and secondary metabolite production in medicinal plants.
- **Pest and Disease Control Devices:** Automated sprayers or ultrasonic pest deterrent systems act when sensors detect early signs of pest infestation or disease, reducing crop losses while minimizing chemical usage.

2.3. *Connectivity and Network Systems*

IoT devices in agriculture require seamless data transmission from sensors to central processing platforms. Connectivity technologies form the backbone of the IoT ecosystem, enabling real-time monitoring and decision-making.

- **Wired Connections:** Ethernet or fiber optic cables are used in large greenhouse farms where stable and high-speed communication is required.
- **Wireless Technologies:** Wi-Fi, Bluetooth, Zigbee, LoRaWAN, Narrowband IoT (NB-IoT), and 5G networks are widely used in agricultural fields to transmit data over long distances, often from remote or dispersed locations.

- **Function:** Connectivity ensures continuous communication between devices, enabling data-driven automation and integration with cloud platforms or edge devices.

2.4. *Data Storage and Cloud Platforms*

Data collected from various IoT devices are transmitted to storage systems for organization, management, and long-term analysis.

- **Cloud Storage:** Platforms like AWS IoT, Google Cloud IoT, and Microsoft Azure allow storage and processing of large datasets. Cloud systems facilitate scalability, centralized management, and remote accessibility.
- **Local Storage:** In some cases, data may be temporarily stored on local servers or gateways, reducing dependency on continuous internet access.
- **Function:** Efficient storage and management of data are crucial for historical analysis, trend identification, and predictive modeling in agriculture.

2.5. *Data Analytics and Artificial Intelligence (AI)*

Data analytics and AI are integral components of IoT-enabled agriculture, transforming raw sensor data into actionable insights.

- **Predictive Analytics:** AI algorithms predict crop growth patterns, pest outbreaks, and irrigation needs, allowing proactive management.
- **Decision Support Systems (DSS):** These systems provide real-time recommendations to farmers, such as optimal planting times, nutrient application schedules, and harvesting periods.
- **Machine Learning:** ML models analyze historical and real-time data to identify patterns, optimize inputs, and improve crop yield and quality.

2.6. *User Interface and Dashboard*

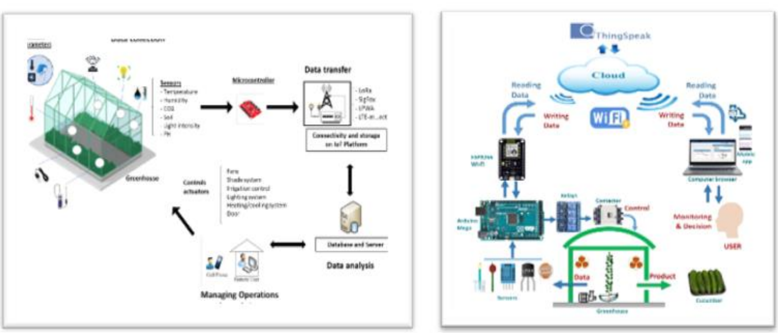
The user interface serves as the point of interaction between farmers and the IoT system.

- **Mobile Apps and Web Dashboards:** Farmers can monitor real-time data, receive alerts, and control actuators remotely. User-friendly dashboards provide visualization of environmental parameters, irrigation schedules, and crop health metrics.
- **Alerts and Notifications:** Automated alerts inform farmers of anomalies, pest attacks, or irrigation needs, enabling timely interventions.

2.7. *Edge Devices and Gateways*

Edge devices and gateways act as intermediaries between sensors and cloud platforms.

- **Function:** These devices perform local data processing, reduce latency, and minimize the volume of data transmitted to the cloud. They enable faster decision-making and reduce bandwidth requirements, particularly in remote farming areas.
- **Example:** An edge controller in a greenhouse can immediately adjust temperature or humidity based on sensor input without waiting for cloud processing.



Plant 1. IoT Architecture diagram for greenhouse sensors

3. Smart Greenhouse Systems for Medicinal Plants

Smart greenhouses integrate IoT technologies to create controlled environments conducive to the cultivation of medicinal plants. Key components include:

- **Climate Control Systems**: Automated systems that regulate temperature, humidity, and light to maintain optimal growing conditions.
- **Soil and Nutrient Management**: Sensors that monitor soil health and nutrient levels, coupled with automated fertigation systems.
- **Pest and Disease Monitoring**: IoT-enabled cameras and sensors that detect early signs of pests and diseases, allowing for timely intervention.
- **Data Analytics and Decision Support**: Platforms that analyze data from various sensors to provide recommendations for crop management.

4. Benefits of IoT-Enabled Smart Farming

The integration of Internet of Things (IoT) technologies into agriculture has transformed traditional farming into a data-driven, precise, and highly efficient practice. IoT-enabled smart farming systems leverage sensors, automated devices, and real-time analytics to optimize the management of crops, soil, water, and nutrients. This approach is particularly beneficial for high-value crops, including medicinal plants, where quality, consistency, and therapeutic efficacy are paramount. The adoption of IoT in agriculture offers multiple benefits, ranging from increased productivity to sustainable resource use and enhanced product quality (Nagar *et al*., 2025; Yong *et al*., 2018).

4.1. Enhanced Resource Efficiency

One of the most significant advantages of IoT-based smart farming is the efficient use of resources such as water, fertilizers, and energy. Precision irrigation systems equipped with soil moisture sensors ensure that crops receive the exact amount of water needed, reducing wastage and conserving water. Similarly, IoT-enabled fertigation systems deliver nutrients in precise quantities based on soil nutrient levels, minimizing excess fertilizer use. Climate control systems in greenhouses adjust heating, cooling, and lighting according to real-time environmental data, thereby optimizing energy consumption. This efficient management of resources is especially important in the cultivation of medicinal plants, where resource optimization directly affects the quality of bioactive compounds (**Singh and Sharma, 2020**).

Plate 2. Modern smart-greenhouse

4.2. Improved Crop Yield and Productivity

IoT-enabled smart farming systems allow farmers to monitor crop growth continuously and intervene proactively whenever necessary. Environmental sensors provide real-time data on temperature, humidity, light intensity, and soil conditions, ensuring that crops grow under optimal conditions. Automated irrigation, nutrient delivery, and climate control reduce stress on plants and promote uniform growth. Studies on medicinal plants such as Ashwagandha

(*Withania somnifera*), Tulasi (*Ocimum tenuiflorum*), and Aloe vera have shown that smart greenhouse systems can significantly improve yield while maintaining high concentrations of active phytochemicals. By optimizing growing conditions, IoT technologies directly contribute to higher productivity and profitability (Singh *et al*., 2025).

4.3. Enhanced Crop Quality

Quality is a critical factor in medicinal plant cultivation, as the therapeutic value of the plants depends on the concentration of bioactive compounds. IoT-enabled smart farming allows precise control over environmental and soil conditions, ensuring that plants produce the desired levels of secondary metabolites, such as alkaloids, flavonoids, and essential oils. Continuous monitoring also enables early detection of nutrient deficiencies, pests, and diseases, preventing stress-induced quality deterioration. Consequently, medicinal plants cultivated under smart farming systems meet higher standards for pharmaceutical, nutraceutical, and herbal product applications.

4.4. Data-Driven Decision Making

IoT systems generate vast amounts of data from sensors and actuators, which can be analyzed using cloud platforms, machine learning, and artificial intelligence. This data-driven approach provides actionable insights, enabling farmers to make informed decisions on irrigation scheduling, fertilization, pest control, and harvesting. Predictive analytics can forecast crop growth, pest outbreaks, and environmental risks, allowing proactive interventions that prevent crop losses. Decision support systems (DSS) further simplify complex data for farmers, enhancing management efficiency and reducing dependency on guesswork.

4.5. Sustainability and Environmental Conservation

IoT-enabled smart farming promotes sustainable agricultural practices by reducing water and nutrient wastage, minimizing chemical usage, and optimizing energy consumption. Precision farming reduces environmental pollution from runoff and leaching of fertilizers and pesticides. Moreover, the ability to cultivate high-value medicinal plants in controlled environments alleviates pressure on wild populations, supporting biodiversity conservation and the sustainable use of natural resources. By integrating sustainability into crop production, IoT technologies align agricultural practices with environmental and policy objectives.

4.6. Labor Efficiency and Automation

Smart farming reduces labor dependency by automating routine tasks such as irrigation, fertilization, and climate control. Automation not only saves time and reduces labor costs but also ensures consistent and accurate execution of farming practices. This is particularly beneficial for large-scale cultivation of medicinal plants, where manual management of environmental conditions and nutrient supply is labour-intensive and prone to errors.

4.7. Market Competitiveness and Profitability

IoT-enabled farming enhances the overall value proposition of agricultural products. Higher yields, consistent quality, and optimized resource use increase profitability for farmers. Additionally, real-time monitoring and data analytics provide traceability and quality assurance, which are essential for meeting domestic and international market standards. This is particularly advantageous in the medicinal plant sector, where product quality directly influences market demand and price.

5. Challenges and Limitations

The integration of Artificial Intelligence (AI) into medicinal plant cultivation offers significant potential for improving yield, quality, and sustainability. AI systems, when combined with IoT-enabled smart farming, allow precise monitoring and management of environmental conditions, soil health, irrigation, and nutrient supply. Despite these advantages, the adoption of AI in medicinal plant cultivation faces several challenges and limitations that must be addressed to ensure effective implementation. These challenges span technical, economic, infrastructural, and socio-cultural dimensions (Sharma *et al*., 2025).

5.1. High Initial Investment and Operational Costs

One of the primary limitations of AI in medicinal plant cultivation is the high initial cost associated with implementing AI-based systems. Establishing a fully automated greenhouse with AI-enabled sensors, climate control systems, data analytics platforms, and connectivity infrastructure requires substantial capital investment. Small-scale farmers, who form a significant portion of medicinal plant cultivators, often lack the financial resources to adopt these technologies. Additionally, ongoing operational costs for system maintenance, software subscriptions, and sensor calibration can be prohibitive, limiting the widespread adoption of AI in this sector.

5.2. Technical Expertise and Training

The effective deployment of AI technologies requires specialized technical knowledge in data analytics, machine learning, and system integration. Farmers and farm managers may lack the necessary skills to operate, troubleshoot, or interpret AI-driven systems. Misinterpretation of AI-generated insights or improper system calibration can lead to suboptimal crop management, affecting yield and phytochemical quality. Continuous training and capacity building are essential to ensure that AI technologies are used effectively, which can be both time-consuming and costly.

5.3. Data Limitations and Quality Issues

AI systems rely heavily on large volumes of high-quality data to make accurate predictions and recommendations. In medicinal plant cultivation, comprehensive datasets on growth patterns, environmental responses, nutrient requirements, and phytochemical profiles are often limited or inconsistent. Variability in soil types, climate conditions, and plant genotypes further complicates data collection. Poor-quality or insufficient data can lead to inaccurate predictions, suboptimal irrigation and fertilization schedules, and reduced overall efficiency.

5.4. Connectivity and Infrastructure Challenges

AI-enabled smart farming systems depend on robust internet connectivity to transmit data from sensors and edge devices to cloud-based analytics platforms. Rural farming regions, where many medicinal plants are cultivated, often face limited or unreliable internet access. Power supply interruptions and lack of adequate infrastructure for data storage and computing can further hinder the functionality of AI systems. Without reliable connectivity, real-time monitoring and decision-making become challenging, reducing the effectiveness of AI-driven interventions.

5.5. Integration with Traditional Knowledge

Medicinal plant cultivation often relies on traditional knowledge regarding plant growth, harvesting, and therapeutic quality. AI systems may not fully incorporate this indigenous knowledge, potentially overlooking local practices that influence plant quality and sustainability. Integrating AI with traditional practices requires careful calibration and collaboration between data scientists, agronomists, and local farmers, which can be complex and time-intensive.

5.6. Regulatory and Ethical Concerns

The use of AI in agriculture raises regulatory and ethical issues. Data privacy, intellectual property rights, and ownership of AI-generated insights are critical concerns, especially when third-party service providers manage cloud-based analytics platforms. Additionally, reliance on AI may reduce human oversight, potentially causing errors in crop management decisions if systems malfunction or provide misleading recommendations.

6. Future Directions

The integration of Artificial Intelligence (AI) into medicinal plant cultivation is still in its nascent stages, yet it holds enormous potential to revolutionize the sector. As demand for high-quality, therapeutically potent medicinal plants grows, AI can play a crucial role in enhancing yield, quality, and sustainability. Future research and development are likely to focus on several key areas to maximize the benefits of AI while addressing current limitations.

6.1. Integration with IoT and Smart Greenhouses

Future AI applications will increasingly be integrated with IoT-enabled smart greenhouse systems. Combining AI with real-time sensor data allows predictive analytics for environmental control, automated irrigation, and nutrient management. This integration will enable precise monitoring of soil moisture, light intensity, temperature, and humidity, ensuring optimal growth conditions for medicinal plants like Ashwagandha (*Withania somnifera*), Tulasi (*Ocimum tenuiflorum*), and Aloevera. Such systems can also predict stress events, pest outbreaks, and disease incidence, enabling proactive interventions that maintain plant quality and therapeutic value.

6.2. Advanced Machine Learning for Phytochemical Optimization

AI can be used to model the relationship between environmental conditions, cultivation practices, and phytochemical content. Machine learning algorithms can analyze historical and real-time data to identify the optimal conditions for maximizing bioactive compound production. Future research may focus on species-specific AI models to enhance alkaloid, flavonoid, curcumin, and essential oil content in medicinal plants, thereby improving the consistency and efficacy of herbal products.

6.3. Integration with Genomic and Biotechnological Data

The future of AI in medicinal plant cultivation will involve integrating genomic, metabolomic, and transcriptomic data with environmental and agronomic data. This approach can facilitate precision breeding and selection of high-yielding, disease-resistant, and bioactive-rich plant varieties. AI-driven predictive models may help identify genotypes with superior phytochemical profiles and resilience to climate variability, accelerating breeding programs and reducing reliance on trial-and-error methods.

6.4. Decision Support and Automation Platforms

AI-powered decision support systems (DSS) will provide farmers with actionable recommendations for crop management, harvesting, and post-harvest processing. Automation platforms integrated with AI can control irrigation, fertilization, and climate systems, reducing labor dependency and human error. Future developments may include mobile-based applications with predictive analytics, enabling smallholder farmers to adopt AI technologies affordably and effectively.

6.5. Sustainability and Conservation

AI can also contribute to sustainable cultivation practices by minimizing resource wastage, reducing chemical inputs, and supporting biodiversity conservation. Predictive AI models can optimize the use of water and nutrients while reducing pressure on wild populations of medicinal plants, aligning cultivation practices with environmental sustainability goals.

7. Conclusion

The integration of IoT technologies into smart greenhouse systems offers a transformative approach to the cultivation and conservation of Ayurvedic medicinal plants. By optimizing environmental conditions and resource use, IoT-enabled systems can enhance the growth, yield, and quality of medicinal plants. While challenges exist, supportive policies and continued technological advancements can overcome these barriers. The collaboration between traditional knowledge and modern technology holds the potential to ensure the sustainable and profitable cultivation of medicinal plants for future generations.

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