Review Article

Precision Agriculture Technologies for Better Production of Medicinal and Aromatic Plants: A Comprehensive Review

Ali Sabah Alhasan[1*], Ali Fadaam Almehemdi[2], Raad Farhan Shahad[3], Hayder Abbas Drebee[1], Dalal Tareq Al-Ameri[4], Osama Majeed Hilal[5], Alaa Taima[5], Dhafer Alhajim[5], Hayyawi W.A. Al-Juthery[3] and Raid Shaalan Jarallah[3]

[1]Department of Horticulture Sciences, Agricultural College, University of Al-Qadisiyah, Al Diwaniyah, 58002, Iraq; [2]Department of Conservation Agriculture, Center of Desert Studies, University of Anbar, Al Anbar, Iraq; [3]Department of Soil and Water Resources, Agricultural College, University of Al-Qadisiyah, Al Diwaniyah, 58002, Iraq. ; [4]Department of Plant Protection, Agricultural College, University of Al-Qadisiyah, Al Diwaniyah, 58002, Iraq; [5]Department of Computer Science, Faculty of Computer Science and Information Technology, University of Al-Qadisiyah, Al Diwaniyah, 58002, Iraq.

Abstract | Medicinal and Aromatic Plants (MAPs) are widely used in traditional medicine and food industries, forming an important part of the global bioeconomy. Yet, their cultivation often suffers from low yields, inconsistent phytochemical composition, and vulnerability to environmental stress, largely because of continued reliance on conventional farming methods. Precision agriculture (PA) offers a promising approach to addressing these challenges through advanced technologies such as remote sensing, unmanned aerial vehicles (UAVs), geographic information systems (GIS), Internet of Things (IoT) sensors, variable-rate input systems, and automation. Recent research indicates that these technologies can optimize irrigation and fertilization, maintain consistent production of bioactive compounds, enhance uniformity in plant growth, and minimize input losses while increasing yield and quality. Several studies have also reported notable improvements in water-use efficiency, essential oil content, and early disease detection, demonstrating both the economic and environmental benefits of adopting smart farming practices. However, large-scale application of precision agriculture (PA) in medicinal and aromatic plant (MAP) production is still limited due to different factors, such as high initial costs, limited species-specific standardization, poor infrastructure, and low digital literacy among growers. This review examines recent developments in the application of precision technologies in MAP cultivation, assesses their advantages and limitations, and highlights future directions for the development of affordable solutions for growers. Integrating precision agriculture into MAP production is important for ensuring quality and competitiveness in global markets on a sustainable basis.

Received | January 04, 2026; **Accepted** | February 17, 2026; **Published** | July 06, 2026
***Correspondence** | Ali Sabah Alhasan, Department of Horticulture Sciences, Agricultural College, University of Al-Qadisiyah, Al Diwaniyah, 58002, Iraq; **Email:** ali.alhasan@qu.edu.iq
Citation | Alhasan, A.S., A.F. Almehemdi, R.F. Shahad, H.A. Drebee, D.T. Al-Ameri, O.M. Hilal, A. Taima, D. Alhajim, H.W.A. Al-Juthery and R.S. Jarallah. 2026. Precision agriculture technologies for better production of medicinal and aromatic plants: a comprehensive review. *Sarhad Journal of Agriculture,* 42(3): 1246-1263.
DOI | https://dx.doi.org/10.17582/journal.sja/2026/42.3.1246.1263
Keywords | Precision agriculture, Medicinal and aromatic plants, Smart farming, Sustainable cultivation, Digital agriculture technologies

Introduction

Presently, medicinal and aromatic plants (MAPs) have become a vital segment of the global botanical economy due to their diverse uses in pharmaceutical, nutraceutical, cosmetic, pesticidal, and food industries (Singh *et al*., 2024; Ahmed *et al*., 2025; Zamani *et al*, 2025). In this modern period, approximately 80% of the world's population is dependent on traditional plant-based remedies for primary healthcare (WHO, 2023). The ever-increasing demand for natural therapeutics, plant-derived ingredients, and ecological sustainability has significantly expanded the scope of medicinal and aromatic plants across the globe. However, cultivation of such medicinal plants continuously faces challenges such as undefined agronomic practices, suboptimal input application, quality inconsistency, and harsh environmental conditions (Singh *et al*., 2021; Pandey *et al*., 2023).

Fluctuations in yield and the accumulation of secondary metabolites of medicinal plants have been observed due to traditional agronomic practices (Alami *et al*., 2024). These fluctuations are mainly characterized by differences in soil fertility, climatic conditions, and cultural practices across the globe. Due to suboptimal cultivation protocols, not only does it limit the productivity, but also directly compromises the pharmacological uniformity and commercial reliability of MAP-derived products and indirectly affects quality (Yousefzadeh *et al*., 2022). Modern techniques have become unavoidable for the production of medicinal and aromatic plants on a sustainable basis, due to a massive increase in demand (Marcelino *et al*., 2023; Chen, 2025; Mahato *et al*., 2025).

The idea of precision agriculture (PA), also termed site-specific crop management, presents a modern strategy to enhance the efficiency of available resources on long-term sustainability for medicinal and aromatic plant (MAP) cultivation. This technique integrates digital and automated tools such as remote sensing, global positioning systems (GPS), unmanned aerial vehicles (UAVs), geographic information systems (GIS), Internet of Things (IoT) sensors, and artificial intelligence (AI) to continuously observe field conditions and guide the application of inputs (Pandit *et al*., 2026). Through real-time data collection and analysis, PA supports informed decision-making that improves the effectiveness of fertilizers and irrigation, stabilizes crop yield and quality, and reduces adverse environmental impacts (Gebbers and Adamchuk, 2010; Jawad *et al*., 2022; Zhou *et al*., 2023; Kumar *et al*., 2025).

Positive response of medicinal and aromatic plants (MAPs) has been recorded when grown under controlled and precision agriculture practices, as their growth and secondary metabolite accumulations are highly influenced by microclimatic shifts as well as soil fertility dynamics (Jampílek and Kráľová, 2023). Water-use efficacy can be improved through the deployment of smart irrigation systems equipped with soil moisture sensors, as done in drought-susceptible species such as *Withania somnifera*. Likewise, the application of spectral or hyperspectral imaging technologies enables early identification of nutrient imbalances and pest infestations in genera such as *Ocimum*, *Mentha*, and *Lavandula* (Kour and Rana, 2020; Rana *et al*., 2022). In addition, machine-learning and artificial-intelligence-driven predictive models can help determine the optimal harvest stage to maximize essential oil concentration and other key phytochemicals, thereby improving both biochemical yield and market value (Patel *et al*., 2021; Varghese *et al*., 2025).

Despite these benefits, there is limited integration of precision agriculture in MAP cultivation. Major limiting factors include high initial costs, lack of infrastructure in rural production zones, limited digital literacy among farmers, technical staff, and insufficient species-specific calibration models for PA tools (Dajic-Stevanovic and Pljevljakusic, 2015; Aulakh and Malhi, 2021). Additionally, there is a scarcity of consolidated research reviewing the applicability, benefits, and bottlenecks of precision agriculture in the context of MAPs.

Therefore, this review aims to critically study the current landscape of precision agriculture approaches as applied to medicinal and aromatic plant production. It explores the technological tools available, evaluates field-based evidence, highlights specific needs and challenges linked with MAPs (Ahmadi *et al*., 2025), and proposes future directions for technology integration. This synthesis seeks to provide a foundational perspective for researchers, agronomists, and policymakers interested in improving performance, sustainability, and quality of MAP cultivation through precision agriculture.

Overview of precision agriculture

Precision agriculture is a science-based strategy to farm management that highlights site-specific interventions to optimize crop productivity while efficiently utilizing inputs and being sustainable and eco-friendly. PA integrates real-time data collection, spatial variability analysis, and automated decision making; it provides a chance to transform farming systems through greater resource efficiency and sustainability (Gebbers and Adamchuk, 2010; Getahun *et al*., 2024). Although its application is well-established in cereals and other cash crops, the incorporation of PA approaches into the cultivation of medicinal and aromatic plants (MAPs) is still at an initial stage (Hernández-Bolaños *et al*., 2025).

Basically, MAPs differ from conventional food crops in their production objectives. The focus in MAP cultivation lies in the biosynthesis of bioactive constituents such as essential oils, alkaloids, flavonoids, and terpenoids rather than in biomass yield. These secondary metabolites are highly sensitive to biotic and abiotic stresses, including soil fertility, water availability, microclimate conditions, and plant protection measures. Slight diversity in agronomic practices can notably change the concentration and composition of important bioactive compounds (Yousefzadeh *et al*., 2022; Pandey *et al*., 2023; Arenas-Salazar *et al*., 2024). Consequently, optimized environmental conditions and good agronomic practices are imperative to safeguard quality assurance, especially for plants used in pharmacopoeias and certified herbal products.

Various techniques are being used for precision agriculture in medicinal and aromatic plant cultivation. Multispectral imaging from UAVs or satellites is a prominent example of remote sensing used to detect initial physiological stress, disease outbreaks, and drought, assessed through vegetation indices. These techniques offer assessment of crop performance on a large scale and non-destructively, with advanced decision of irrigation and nutrient application (Rana *et al*., 2022). Furthermore, IoT soil sensors offer nonstop real-time data on parameters like pH of the soil, moisture, and salinity level, which are necessary for plants such as *Ocimum sanctum*, *Mentha arvensis,* and *W. somnifera*, to maintain quality and yield of essential phytochemicals (Prasanna *et al*., 2024).

Field variations can be assessed by the growers through Geospatial mapping using GPS and GIS technologies. This valuable information enables application of variable rate technologies (VRT), where seeds, fertilizers, and pesticides are applied only where and when needed. These techniques are environmentally friendly and promote uniform plant growth and development, along with constant phytochemical characteristics that are vital for maintaining the therapeutic reliability of medicinal plants (Sharma *et al*., 2023). Moreover, a blend of environmental modeling with artificial intelligence and machine learning algorithms can forecast pest occurrences or harvest indices for optimal phytochemicals accumulation (Kour and Rana, 2020; Jawad *et al*., 2022; Maryam *et al*., 2025).

Although these techniques have a notable impact on the cultivation of MAP but still, due to certain limitations like lack of awareness among MAP growers, the absence of species-specific calibration data for sensors, inadequate digital infrastructure in distant cultivated areas and high initial investment, restricts its application. Furthermore, since MAPs are often cultivated in marginal environments by smallholder farmers, adoption of high-tech approaches requires context-specific adaptation and capacity-building interventions (Aulakh and Malhi, 2021). In conclusion, while precision agriculture holds considerable promise for improving the yield and quality of medicinal and aromatic plants, its implementation must be guided by localized research, cost-effective tools, and participatory technology transfer.

Relevance of precision agriculture in MAP cultivation

Medicinal and aromatic plants (MAPs) play a vital role in both traditional and modern healthcare systems, as well as in pharmaceutical, cosmetic, and food industries. Globally, more than 53,000 species of plants are being used for medicinal purposes, and approximately 3,000 species are traded on a commercial level, with a market growth rate of 6-8% annually (WHO, 2023; Zamani *et al*., 2025). India is one of the major contributors to the supply chain of medicinal and aromatic plants, as it shares around 7,000 species, out of which approximately 1,200 are commercially important, with popular crops including *W. somnifera*, *O. sanctum*, *M. arvensis*, *A. vera,* and *R. damascena* (NMPB, 2022; Ahmed *et al*., 2025). Apart from their importance, production systems for most MAPs remain suboptimal, often forced by poor agronomic practices, fragmented cultivation areas, low productivity, and fluctuations in the quality of phytochemicals.

Precision agricultural interventions are adoptable for the production of medicinal and aromatic plants due to their inherent sensitivity to environmental variables. In contrast to food crops, where yield is measured in terms of biomass, medicinal plants are valued for their ability to accumulate phytochemical compounds. Quantification and quality of phytochemical profile such as alkaloids, essential oils, glycosides, and phenolics in medicinal plants, are mainly influenced by local environmental and agronomic practices, including maintaining soil fertility, pest control, and water availability to medicinal plants (Yousefzadeh *et al*., 2022). Notable variation was observed in menthol contents in *Mentha* species in response to various levels of nitrogen and irrigation (Rathi *et al*., 2020). Similarly, linalool and eugenol contents in *Ocimum basilicum* were affected by plant population, light duration, and nutrient status of soil (Saxena *et al*., 2021). These variables highlight the significance of precision agriculture approaches that enable real-time observing and targeted management of these growth-determining factors.

Modern approaches like remote sensing, Internet of Things (IoT)-based soil and crop sensors, and variable rate input systems, provide continuous and site-specific data that help real-time management of medicinal plant fields. In aromatic crops like *R. damascena*, thermal imaging through unmanned aerial vehicles (UAVs) has been efficiently utilized to sense drought and finalize irrigation schedules, resulting in improved flower yield and higher essential oil recovery (Bakhshi *et al*., 2022). Similarly, the application of sensor-guided fertigation systems in *W. somnifera* cultivation has been described to promote root development and increase withanolide concentration through maintaining optimal nutrient supply during the entire growth period (Kumar *et al*., 2022a).

The commercial importance of these approaches is increasingly reflected in the expanding global trade of medicinal and aromatic plants (MAPs). The essential oils sector alone had a trade of approximately USD 9.5 billion in 2021, and it was predicted to reach

Table 1: *Applications of GIS techniques in medicinal and aromatic plant (MAP) cultivation.*

MAP Species	GIS Application	Precision Benefit	Reference
Rosa damascena	Slope and elevation mapping using DEM	Improved site selection for oil-rich flowers	Kumar *et al*., 2022
Mentha arvensis	Nitrogen application zone delineation	Enhanced menthol content and reduced N loss	Saxena *et al*., 2021; Gulati *et al*., 2025
Withania somnifera	Climate suitability modeling	Identification of new suitable growing regions	Sharma *et al*., 2023
Acorus calamus	Soil drainage and fertility mapping	Optimized planting site selection	Pandey *et al*., 2023
Ocimum basilicum	Geo-referenced pest outbreak tracking	Targeted pesticide application and reduced residue	Bakhshi *et al*., 2022
Aloe vera	GPS-assisted harvest scheduling	Quality maintenance and labor efficiency	Rana *et al*., 2022

Table 2: *Applications of variable rate technology (VRT) in medicinal and aromatic plant (MAP) cultivation.*

Crop	VRT Application	Observed Outcome	Study/Source
Mentha arvensis	Variable nitrogen fertilizer dosing	Increased menthol yield, reduced N leaching	Singh and Bansal, 2019
Ocimum basilicum	VRT-based irrigation scheduling	Improved linalool concentration, enhanced WUE	Rahimi and Gholami, 2020
Cymbopogon flexuosus	Precision pesticide application	Targeted pest control, lower residue in essential oils	Alam *et al*., 2021
Withania somnifera	Variable compost application	Higher withanolide content and biomass uniformity	Kapoor and Desai, 2022
Aloe vera	VRT micronutrient foliar spraying	Increased aloin concentration, optimized nutrient use	Shakya *et al*., 2018
Lavandula angustifolia	Targeted drip fertigation	Increased oil yield and improved plant health	Mahmoodi and Tabrizi, 2021

around 15 billion USD in 2027, primarily powered by growing consumer demand for best, residue-free, and sustainably produced products (Markets and Markets, 2022). Countries like India, China, and Egypt are dominating the medicinal plant products export sector, and are increasingly recognizing the significance of integrating digital and precision cultivation methods to meet international standards and quality.

Moreover, climate change is the main threat to medicinal plant cultivation, but precision agriculture provides a way to climate resilience. Tools like predictive analytics and AI-based decision support systems can help in detecting disease risks, predicting irrigation needs, and recommending adaptive responses based on localized Wheater forecast, necessary for medicinal plants as their cultivation in made in ecologically sensitive zones or rain-fed areas, where crop failure or suboptimal growth can result in notable economic losses (Pandey *et al*., 2023).

Application of precision agriculture, in the cultivation of medicinal plants, aligns with dual objectives of enhancing phytochemical yield and ensuring sustainability. By enabling real-time, site-specific management, PA not only enhances the agronomic performance of MAP cultivation but also helps to meet global demand for optimized, high-quality plants and products. As the sector moves toward greater commercialization and regulatory oversight, precision agriculture will be contributory in updating

Table 3: *Applications of AI and decision support systems in medicinal and aromatic plant (MAP) cultivation.*

MAP Species	AI/DSS Technology Used	Practical Outcome	Reference
Ocimum basilicum	SVM model for oil yield prediction	Site-specific fertigation scheduling	Bhatnagar *et al*., 2022
Withania somnifera	CNN for disease classification	Rapid identification of leaf spot and wilt symptoms	Alam *et al*., 2021
Mentha spicata	Random Forest model using weather and soil data	Predictive analysis of essential oil variability	Devi *et al*., 2022
Cymbopogon flexuosus	DSS with IoT + AI models	Optimized irrigation and harvest decisions	Raut and Sharma, 2021; Pandit *et al*., 2026
Lavandula angustifolia	AI-assisted weed recognition system	Reduced manual labor and precise herbicide application	Iqbal *et al*., 2023
Aloe vera	Blockchain + AI-enabled traceability module	Quality control and certification for export markets	Joseph and Chatterjee, 2023

Table 4: *Applications of automation and robotics in the cultivation of medicinal and aromatic plants (MAP).*

MAP Species	Automation/Robotic system	Function and outcome	Reference
Ocimum sanctum	Automated transplanter	Enhanced seedling survival and uniform crop establishment	Menon *et al*., 2020
Aloe vera	Vision-guided robotic harvester	Damage-free leaf collection with improved aloin retention	Gupta and Rao, 2021
Lavandula angustifolia	Autonomous harvesting platform	Precision harvesting at ideal bloom stage, better oil quality	Baral *et al*., 2022
Withania somnifera	Robotic sprayer with disease recognition camera	Fungicide delivery to disease spots, minimal residue formation	Khanna and Bose, 2020
Cymbopogon citratus	Soil sensor robot with EC and moisture probes	Early detection of nutrient stress and variable input mapping	Prasad *et al*., 2023
Mentha arvensis	Robotic inter-row cultivator	Efficient weed removal, reduced herbicide use	Rizvi *et al*., 2022
Curcuma longa	Automated rhizome digger	Improved harvesting efficiency, reduced damage to rhizomes	Singh *et al*., 2020
Rosmarinus officinalis	Autonomous greenhouse climate controller	Optimized humidity and ventilation for higher essential oil biosynthesis	Rahman and Pathak, 2021
Eclipta alba	Robotic seeder with GPS guidance	Uniform planting depth and spacing, synchronized flowering	Verma *et al*., 2023

MAP production systems and safeguarding their long-term practicality.

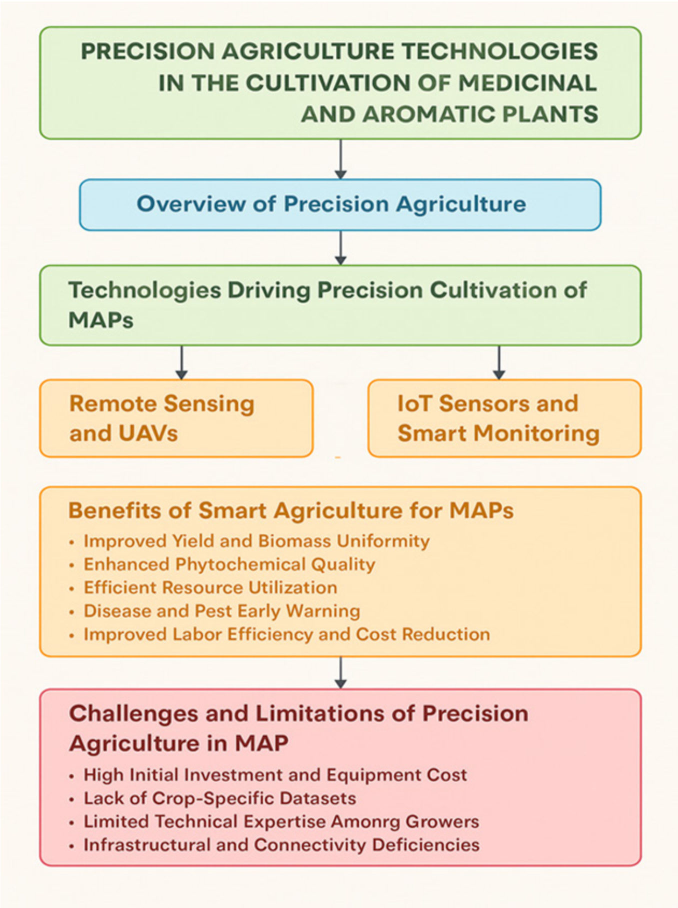

Figure 1: *Illustration of the application of precision agriculture technologies in the cultivation of medicinal and aromatic plants (MAPs), showing key technologies, their benefits, and associated challenges.*

Technologies driving precision cultivation of MAPs

Remote sensing and UAVs

Remote sensing is one of the most innovative approaches in precision agriculture, offering non-destructive, real-time observation of crop and field parameters across varying spatial and temporal scales. Medicinal and aromatic plants (MAPs), which are highly sensitive to slight change climatic conditions, nutrient status, and abiotic stress, remote sensing, particularly via unmanned aerial vehicles (UAVs), provides an efficient method to standardize cultivation approaches and improve the yield and quality of medicinal plants. UAVs, commonly known as drones, are equipped with multispectral, hyperspectral, thermal, and high-resolution RGB sensors. These cargos enable gathering of information about main vegetation indices such as Normalized Difference Vegetation Index (NDVI), Leaf Area Index (LAI), and Photochemical Reflectance Index (PRI), which are skimpy of plant vigor and photosynthetic efficiency (Rana *et al*., 2022). For medicinal plants, these indices are mainly significant due to fluctuations in vegetative vigor that directly influence the synthesis and accumulation of phytochemicals (Bahuguna *et al*., 2022; Yousefzadeh *et al*., 2022).

Research indicates that multispectral imaging using unmanned aerial vehicles (UAVs) can efficiently recognize initial indicators of drought in *Rosa damascena*, allowing timely application of irrigation to avoid decline in flower quality and essential recovery (Bakhshi *et al*., 2022). In *M. arvensis*, through drone-assisted spectral analysis, chlorophyll content was measured. Similarly, quantification of menthol was assessed under various nitrogen levels (Saxena *et al*., 2021; Gulati *et al*., 2025). Similarly, thermal imaging techniques have been effectively used for the detection of heat stress in *O. basilicum*, offering insightful information for the management of canopy temperature and the detection of plant stress factors. This information is also helpful for scheduling irrigation, which leads to a stable essential oil profile and overall quality of medicinal plants (Kour and Rana, 2020; Pineda *et al*., 2020).

IoT sensors and smart monitoring

The backbone of precision agriculture is the Internet of Things (IoT), which enables unified real-time monitoring of crucial stages of crop and environmental attributes (Moghadam *et al*., 2026). In the case of medicinal plants, where consistency in quality and quantity of phytochemicals is mainly dependent on the micro-environment, IoT-based sensor networks offer immense potential to optimize input use. IoT comprises field-deployed sensor nodes, wireless networks, cloud-based data processing systems, and user-oriented interfaces that work collectively to capture and transmit real-time data for informed decision-making. These sensors have the ability to record a diverse set of agro-environmental data, including soil moisture, temperature, electrical conductivity, humidity, due drop intensity, light intensity, and canopy temperature. The collected information is transmitted via wireless networks like LoRa, Wi-Fi, or ZigBee to a central cloud, where advanced analytics transform raw information into actionable recommendations for crop management (Jawad *et al*., 2022; Mohammed and Munir, 2025).

Water use efficacy is based on efficient irrigation

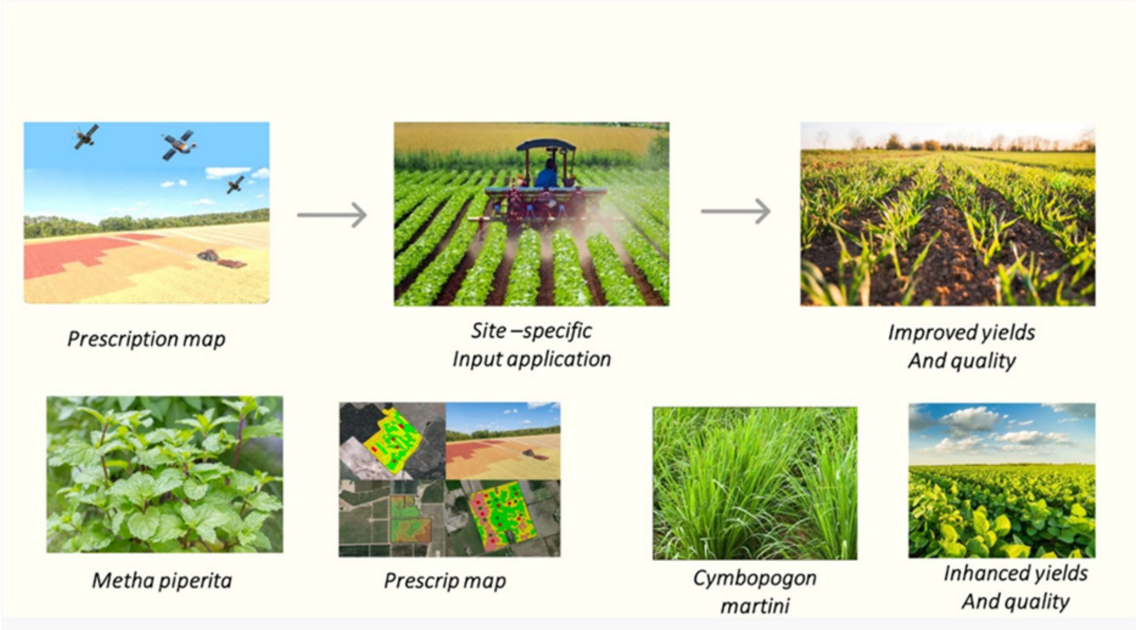

Figure 2: *Different aspects of variable rate technology (VRT) including generation of prescription maps, site-specific input application which results in to enhanced yield and quality of medicinal and aromatic plants such as Mentha piperita and Cymbopogon martini.*

scheduling at the critical growth stage of medicinal plant production, as soil moisture directly influences essential oil recovery and overall plant secondary metabolites. In a case study, observations were recorded that a reduction in soil moisture directly reduced eugenol content in *O. sanctum*; however, excessive irrigation in *M. arvensis* resulted in low oil contents and poor quality (Saxena *et al*., 2021). The application of soil moisture sensors integrated with automated irrigation systems provides accurate regulation of water supply (Meriç, 2025).

Another key area for the application of IoT is nutrient regulation in medicinal and aromatic plant production. Actually, monitoring of essential macronutrients, particularly NPK, can be attained by soil nutrient probes and ion-selective electrode sensors positioned in the rhizosphere. A precise fertilizer application schedule is obtained through the integration of IoT-based systems with local weather forecasts and crop growth simulation models, which improve nutrient uptake efficiency and overall plant vigor. Sensor-controlled fertigation in *W. somnifera* has shown significant improvement in withanolide concentration (Kumar *et al*., 2022). Plant physiological status within the canopy and even at the leaf level can be detected via advanced sensing tools. Continuous monitoring of parameters such as transpiration rate, leaf temperature, and chlorophyll fluorescence provides initial detection of water and nutrient stress before visual symptoms occur, as done in *Aloe vera* (Rana *et al*., 2022). Furthermore, precise monitoring tools play a significant role in pest and disease management of medicinal plant production. It is very important in the case of medicinal plans, where maintaining a residue-free product is essential for therapeutic applications (Kour and Rana, 2020; Li and Wang, 2024).

Geographic information systems (GIS)

Precision agriculture is mainly based on GIS, as it provides the collection, storage, analysis, and visualization of spatial and temporal data from agricultural fields and is helpful in making accurate decisions (Mathenge *et al*., 2022). However, when GIS tools are employed in medicinal plants cultivation, helpful in detecting variation in soil fertility and crop conditions, thus offering informed decision making for specific site management. Generally, medicinal plants are being cultivated on marginal lands while fertile lands are under the cultivation of cash crops. Comprehensive information about the spatial mapping of these fields through GIS technology allows growers to define zones based on variations in soil texture, topography, and fertility (Pandey *et al*., 2023). In the case of *R. damascena* and *Acorus calamus*, Digital Elevation Models (DEMs) have been effectively employed to optimize planting sites to ensure better root development and essential oil recovery (Kumar *et al*., 2022).

Furthermore, GIS tools help integrate different source data, such as images taken from satellites, field sensor data, and UAV maps, to monitor plant growth, pest attacks, and drought. Accurate field operations could be applied through GPS data, which is helpful to manage different field operations like irrigation, fertilizer application, and harvesting at the optimum stage, which are important for maintaining phytochemical yield in medicinal plants such as *M. arvensis*. Nitrogen application zones with the help of GIS have resulted in stable menthol production (Saxena *et al*., 2021).

For the cultivation of high-value medicinal plants, GIS is also helpful for planning and assessing the environmental impact on organically produced medicinal plants. Crop history can also be tracked through spatial databases developed by GIS; furthermore, the application of various inputs and disease outbreak patterns may also be recorded, which is most important for traceability and regulatory compliance (Bakhshi *et al*., 2022). Models such as these incorporate variables such as temperature, rainfall, humidity, and solar radiation to predict potential yield areas and guide expansion approaches. For example, climate suitability mapping has been effectively used to assess future cultivation areas for *W. somnifera* and *O. basilicum* under climate change scenarios (Alam *et al*., 2021a; Sharma *et al*., 2023). Practical implementation of GIS in MAP cultivation, however, requires precise field data, skilled personnel, and supportive digital infrastructure. Limited access to spatial tools in rural areas and the high cost of commercial GIS software can be barriers. Nonetheless, the availability of open-source GIS platforms (e.g., QGIS) and the proliferation of mobile-based GPS applications are making geospatial technologies increasingly accessible to MAP farmers and cooperatives.

Variable rate technology (VRT)

Variable Rate Technology (VRT) enables site-specific application of agricultural inputs like fertilizers, irrigation, and crop protection agents based on real-time data and geospatial analysis. Precision-based method holds significant relevance in the cultivation of medicinal and aromatic plants (MAPs), where spatial variability in soil fertility, microclimate, and crop requirements mainly influences secondary metabolite synthesis and overall crop yield.

The quality of medicinal plant products is affected by uneven application of inputs, i.e., fertilizer and pest control chemicals. Variable Rate Technology (VRT) helps address such challenges by enabling modification of input doses to meet the actual requirement of a crop (Saleem *et al*., 2023). In the case of peppermint (*Mentha piperita*), application of nitrogen fertilizer for a specific zone or site guided by prescription maps notable increase in concentrations of menthol was recorded, and indirectly minimizes the cost of nutrients through precise application (Yadav *et al*., 2021). Similarly, targeted irrigation in *Cymbopogon martinii* using VRT systems improved geraniol yield, a key component of essential oil, by precisely matching water delivery with the crop's peak evapotranspiration demands (Das *et al*., 2022). Similarly, a potassium dose was applied to the ashwagandha (*W. somnifera*), which showed improvement in both withanolide and root biomass (Meena and Solanki, 2020). Furthermore, pest management was made through VRT-equipped sprayer machines, targeting pest holy basil (*O. sanctum*), which resulted in minimizing pesticide which ensure residues are free as per standards demanded by the pharmaceutical industry (Chopra *et al*., 2021). Prevention of nutrient runoff and environmental sustainability can be achieved through the application of Variable Rate Technology (VRT), as medicinal plants are being cultivated in environmentally sensitive zones across the globe, which is why it is important for sustainability. VRT offers a uniform phytochemical composition, which highlights its significance in medicinal plant production (Mishra and Patra, 2023; Chen, 2025).

Apart from its confirmed advantages, the application of Variable Rate Technology (VRT) in the cultivation of medicinal and aromatic plants is still limited due to several constraints. Main factors include installation cost, limited geospatial data, and inadequate technical training for growers. Moreover, mostly VRT systems are built for large-scale farming and crop-specific, while monoculture farming, making them difficult to adapt to smallholder operations typical of MAP cultivation. Therefore, developing the cheapest and customized VRT solutions can maximize their application for revolution in the field of medicinal and aromatic plant production on a sustainable basis.

Artificial intelligence and machine learning

Artificial Intelligence (AI) and Decision Support Systems (DSS) are playing an increasingly transformative role in the global landscape of

Medicinal and Aromatic Plant (MAP) production. Yield and crop management for a specific place can be assessed for growers and researchers could be possible through artificial intelligence (Maryam *et al*., 2025). Sustainability in yield and phytochemicals is necessary for the medicinal and aromatic plant production, within a limited production cost, which is possible through AI tools. Multisource data like spectral imagery, meteorological forecasting, and soil moisture could be analyzed through AI tools, including Deep Learning (DL), Machine Learning (ML), and fuzzy logic. For instance, in specific medicinal plants like sweet basil (*O. basilicum*) and spearmint (*Mentha spicata*), supervised ML models have been successfully employed to assess the yield of biomass and essential oil content based on integrated environmental and cultivation attributes (Singh *et al*., 2023).

Convolutional Neural Networks (CNNs) have shown high efficiency when used for the identification of diseases and pests in different crops, such as *W. somnifera* and *Lavandula angustifolia*, using image-based categorization. Production losses can be minimized through early identification of pathogens and abiotic stress symptoms through AI tools and timely application of agrochemicals and organic compliance, often required for export-grade MAPs (Tiwari *et al*., 2022). Decision Support Systems (DSS) and AI algorithms work together as they are integrated with agronomic databases, remote sensing, and climate predictions. For example, decision support systems tools particularly developed for *Cymbopogon flexuosus* plantations in India use soil moisture sensors, evapotranspiration, precision pesticidal delivery system, and weather forecasts to help determine when and how much irrigation water is needed to apply, which directly affects geraniol content in essential oils (Alam *et al*., 2021b; Panda *et al*., 2023).

Monitoring, traceability, and quality are also improved through AI. Integration of smart labels and blockchain technologies with AI permits tracking of product origin, inputs, and batch characteristics. This guarantees authenticity in MAP supply chains, particularly for high-value crops like *Aloe vera* and *Boswellia serrata*, which are liable to contamination. Despite their potential, AI adoption in MAP farming is limited by the unavailability of crop specific database, a lack of digital knowledge among growers, and cost barriers. Collaborations between research organizations, government programs, and tech companies are important to develop open-access tools and low-cost decision platforms customized for medicinal and aromatic plants growers.

Automation and robotics

Integration of automation and robotics into precision agriculture has opened new horizons for improving efficiency, precision, and labor optimization in the cultivation of medicinal and aromatic plants. These technologies enable site-specific operations such as transplanting, harvesting, spraying, and monitoring, especially critical for high-value crops that demand minimal contamination, uniformity, and the best harvest timing. Medicinal plants require delicate handling to preserve the integrity of bioactive compounds. For example, robotic harvesters equipped with soft grippers and vision systems have been developed to selectively pick *Aloe vera* leaves based on their maturity index, ensuring maximum aloin content while avoiding damage to younger leaves (Gupta and Rao, 2021; Mitra *et al*., 2022). Harvesting of *L. angustifolia* flowers through automated harvesting platforms has significantly increased harvesting speed and oil recovery by avoiding over-mature or underdeveloped flowers.

Automated mechanical transplanting systems are getting popular for medicinal and aromatic plants nurseries, especially for crops such as *O. sanctum*, *Mentha* spp., and *Eclipta alba*. As these systems ensure uniform plant distance, minimize transplanting shock, and help establish early crop uniformity, which is important for synchronized flowering and sustainable essential oil profiles (Nayyar *et al*., 2021). Similarly, robotic sprayers are making a notable impact on the efficacy of the spraying process in disease and pest management. These tools can autonomously navigate in the fields using GPS and LiDAR technologies and are capable of efficient spraying for pest and disease control in medicinal fields. Fungal infection in *W. somnifera* fields can damage the root biomass production up to a notable level. Automated sprayers equipped with multispectral cameras have been used to detect disease and spray fungicides with high precision (Choudhary and Das, 2023).

Robotic platforms have significantly advanced the monitoring of crops and the analysis of agricultural soils. Ground-based rovers, integrated with multi-sensor arrays, are used to collect soil samples, monitor temperature, moisture, and electrical conductivity, and identify nutrient-deficient patches in real-time. These robots have been especially useful in evaluating micro-site variability in *Cymbopogon* and *Vetiveria* plantations established on degraded lands. Although the initial investment for robotic solutions is high, their long-term benefits, such as consistent quality, reduced labor dependency, and efficient resource use, are driving adoption, particularly among commercial MAP growers and cooperatives. Affordable, small-scale automation solutions are also being developed for smallholder applications in developing countries.

Case Studies and Applications

Practical application of technologies in precision agriculture for the cultivation of medicinal plants has developed in recent years; various case studies have been conducted in this regard for the assessment of its significance. These case studies showcase how different tools aligned with sensors, remote monitoring, variable rate inputs, and automation improve yield and quality with minimal cost of production.

India: Lemongrass and holy basil in the indo-gangetic plains

Extensive cultivation of *C. flexuosus* (lemongrass) and *O. sanctum* (holy basil) plantations have made in India's Indo-Gangetic plains. For irrigation IoT systems with combination of soil moisture sensors has been adopted, resulting in up to 30% water saving through this integration without compromising oil yield and phytochemical profile. Furthermore, NDVI imaging technology was used to optimize nitrogen use, which resulted in a 15–20% increase in oil content per hectare (Das *et al*., 2022). These technologies were adopted through cooperation of the National Medicinal Plants Board (NMPB), aiming to make MAP farming profitable and sustainable.

Morocco: Saffron cultivation in arid highlands

Remote sensing and UAVs were used in the Talioune region of Morocco for monitoring to assess plant vigor and drought in terraced fields of *Crocus sativus* (saffron). Satellite imagery, paired with ground validation, facilitate to identify micro-zones requiring additional irrigation. Flowering is associated with precision nutrient mapping, which improves flower intensity, but with the deployment of remote sensing, phosphorus application was reduced up to 28% without compromising crocin concentration (El Fadili *et al*., 2021).

China: Panax notoginseng under greenhouse automation

Panax notoginseng is an important medicinal plant, cultivated in controlled conditions in Yunnan Province, China. AI helps in decision-making based on soil moisture, humidity, temperature, and disease-identifying sensors were integrated. Real-time alerts helped growers in operating foggers, fungicide sprays, and ventilation management as needed. Chemical inputs were reduced up to 42% and improved ginsenoside consistency in all batches. The initiative was part of a provincial smart farming trial by Kunming Institute of Botany (Zhang *et al*., 2023).

Italy: Lavender and rosemary fields in mediterranean agroecosystems

Autonomous harvesting of *L. angustifolia* and *R. officinalis* fields in Tuscany was adopted. Harvesting time was optimized with the help of these autonomous tools by detecting peak bloom and oil content windows without wastage of time. Adoption of variable rate fertigation also enhanced essential oil density while reducing nitrogen level up to 18%. Regional cooperatives supported training in precision agriculture technologies to reduce manual labor dependency and increase product traceability (Ricci *et al*., 2020).

Brazil: Aloe vera and native MAPs in the semi-arid caatinga

Solar driven smart irrigation system was adopted for the cultivation of *Aloe vera* by a small landholder of sami-arid Caatinga region. These systems, connected to mobile DSS platforms, monitored water requirement based on solar radiation and crop phenology. Improved irrigation efficiency improved aloin content and minimized root rot occurrences. Trials on native MAPs like *Lippia sidoides* also established improved thymol yield through sensor-guided fertilization (Silva *et al*., 2021).

Challenges and limitations

Precision Agriculture (PA) promises to improve the efficiency and sustainability of medicinal and aromatic plant (MAP) production. However, its extensive adoption is hindered by several interrelated technical, economic, and infrastructural challenges that are especially pronounced in medicinal and aromatic plants systems compared to major cereal crops (Ahmadi *et al*., 2025).

High initial investment and equipment cost

One of the principal limitations is the significant upfront cost associated with PA technologies. These include GPS-guided machinery, variable rate applicators, UAVs, multispectral cameras, and soil-sensing equipment. Many MAPs, such as *Ocimum*, *Vetiveria*, and *Lemongrass*, are cultivated in small-scale systems where return on investment is marginal. In a recent study across herbal cooperatives in Nepal and northern India, 78% of growers reported that PA equipment was unaffordable without external subsidies (Shrestha *et al*., 2022; Manickam *et al*., 2023). Furthermore, PA manufacturers often tailor equipment to large-scale monocultures, leaving MAP growers without appropriate, cost-effective models.

Lack of crop-specific data and models

The major limiting factor is the unavailability of crop-specific spectral databases, nutrient thresholds, and yield prediction models for most MAPs. While a database exists for cereals and vegetables, few calibration datasets are available for *Ashwagandha*, *Tulsi*, *Kalmegh*, or *Sarpagandha*. This limits the precision of machine learning algorithms, remote sensing indices, and fertigation models when applied to MAPs (Olatunji *et al*., 2023; Figueroa *et al*., 2022). Furthermore, even in greenhouse MAP systems, uniformity in phenological modeling is missing, complicating automation protocols.

Limited digital and agronomic literacy

Digital literacy among growers remains a major constraint. Many smallholder MAP farmers are unfamiliar with data interpretation, app-based watching, or cloud-connected platforms. In a study of *M. arvensis* and *A. vera* cultivators in eastern Uttar Pradesh, only 18% of respondents had used mobile-based DSS platforms and 62% relied solely on visual cues for crop decisions (Tariq *et al*., 2022; Rathod *et al*., 2021). Extension agents often lack updated training in PA tools, leading to a mismatch between available technology and on-ground support.

Infrastructure and connectivity gaps

Use of sensor-driven systems and cloud-connected tools requires stable internet, GPS signals, and regular power supply conditions that are often missing in remote MAP-growing regions. In Ethiopia, for example, high-value aromatic species such as *Eucalyptus citriodora* and *Thymus schimperi* are being cultivated in rural areas where connectivity issues restrict the use of automated irrigation and remote field sensing (Tadesse *et al*., 2022).

Weak integration with quality certification systems

Precision agriculture systems can generate valuable traceability and quality assurance data. However, many certification bodies still depend on manual documentation. Absence of standardization in Precision agriculture outputs means that current data often cannot be directly applied for certification or export documentation, limiting growers' motivation to adopt such systems (Leung *et al*., 2023; Jamwal *et al*., 2023).

Benefits of smart agriculture for MAPs

Application of smart agriculture approaches in the production of medicinal and aromatic plants (MAPs) provides multifaceted advantages that extend beyond productivity improvement. These technologies, including precision irrigation, automated harvesting, disease identification, remote sensing, automated cultivation systems, and artificial intelligence-driven decision tools, permit growers to address unique physiological, environmental, and economic aspects associated with MAP farming.

Improved yield and biomass uniformity

Medicinal and aromatic plant production often targets phytochemical yield rather than biomass alone. Precision agriculture techniques help to optimize input use based on crop requirements, which leads to uniform growth and biomass on a sustainable basis. For example, variable-rate nitrogen application in *M. arvensis* enhanced both biomass and menthol content by associating nutrient availability with the plant's developmental stage (Kumar *et al*., 2022b). Similarly, remote sensing technology has assisted early detection of growth variability in *O. basilicum*, improving field management approaches and leading to a 15% increase in dry matter (Silva *et al*., 2021; Zhong *et al*., 2025).

Enhanced phytochemical quality

Concentration of secondary metabolites in MAPs such as essential oils, alkaloids, and flavonoids is extremely sensitive to environmental conditions. Accurate control of microclimatic conditions through greenhouse automation and real-time observing of soil pH, temperature, and humidity leads to improved phytochemical profiles. In *L. angustifolia*, smart irrigation systems maintained optimal stress levels that improved linalool and linalyl acetate content, both main indicators of commercial oil quality (Tiwari and Joshi, 2023).

Efficient resource utilization
Wastage of resources can be minimized through smart agriculture by enabling need-based applications without compromising yield and quality. In *Cymbopogon citratus*, water use was minimized up to 40% by controlling drip irrigation systems via soil moisture sensors, with no loss in oil yield. Similarly, site-specific herbicide application reduced chemical use by up to 60% in *Rosmarinus officinalis* plantations, where autonomous sprayers targeted only weed-affected zones (Pereira *et al*., 2022).

Disease and pest early warning
Sensor networks and AI-based image analysis facilitate early detection of biotic stress, allowing growers to implement targeted and timely interventions. In *W. somnifera*, spectral imaging systems identified foliar blight at its early stages, leading to a 50% reduction in yield loss compared to the conventional scouting (Raut and Mishra, 2021). The integration of such tools reduces unnecessary pesticide applications and supports organic certification.

Improved labor efficiency and cost reduction
Intensive labor is required in medicinal and aromatic plant production, especially for transplanting, weeding, and harvesting. Automation and robotics minimize the dependency on labor, which is necessary in regions where labor availability is limited. Trials with semi-autonomous harvesters in *Aloe vera* fields showed a 45% reduction in harvesting time and labor cost per hectare (Benitez *et al*., 2023).

Data-driven traceability and market access
With increasing international scrutiny over herbal product authenticity and safety, traceability is becoming a competitive advantage. Smart agriculture allows the generation of verifiable data on cultivation practices, input history, and harvest records. Blockchain-integrated traceability platforms, now emerging in high-value MAPs such as *Panax ginseng* and *Boswellia serrata*, support compliance with WHO-GACP and organic standards, facilitating access to premium export markets (Chakrabarti *et al*., 2022; Zamani *et al*., 2025).

Future perspectives
The intersection of medicinal and aromatic plant (MAP) cultivation with smart agriculture technologies is entering a transformative phase. Although adoption remains uneven, emerging innovations in sensors, artificial intelligence (AI), data integration, and automation are expected to substantially improve yield quality, sustainability, and traceability in MAP production systems. Going forward, addressing infrastructural, socio-technical, and policy-level gaps will be pivotal in realizing the full potential of precision agriculture in this sector.

Development of MAP-specific digital models
There is a clear need for crop-specific modeling tools tailored to the unique physiology and secondary metabolite pathways of MAPs. Investment in AI and machine learning algorithms for forecasting plant growth, essential oil profiles, and disease susceptibility will be essential. Establishing open-access databases containing spectral signatures, growth patterns, and soil interactions for key MAP species (e.g., *O. basilicum*, *Curcuma longa*, *Panax notoginseng*) will enable more accurate and site-specific decision-support systems (Rana *et al*., 2022; Sharma *et al*., 2023).

Scalable and affordable precision tools for smallholders
Future efforts should focus on the design and deployment of low-cost, solar-powered, and modular PA systems that cater to small and marginal MAP growers. This includes simplified IoT kits, SMS-based advisory systems, and smartphone-integrated sensing platforms. Pilot projects in India and Ethiopia have demonstrated the viability of such scaled-down systems in increasing the profitability of MAP production (Binyam *et al*., 2022; Patel and Jain, 2023).

Blockchain and certification integration
Integrating blockchain platforms with sensor-based traceability data can redefine quality assurance mechanisms in the MAP value chain (Joseph and Chatterjee, 2023). These systems should be aligned with the WHO-GACP, USDA Organic, and EU Organic protocols. Transparent digital records from sowing to post-harvest handling can enable seamless audits, build consumer trust, and facilitate access to high-value international markets (Lopes *et al*., 2022; Gurusamy *et al*., 2025).

Multidisciplinary training and capacity Building
Capacity building for medicinal and aromatic plant growers is a key step toward enhancing their ability to use digital tools effectively. This is particularly important in rural and tribal regions where most high-value MAP species are cultivated. To achieve this,

agricultural universities and extension services should design practical training programs and demonstration sessions focused on modern cultivation techniques, the operation of digital sensors, and the use of crop-monitoring technologies (Gupta and Awasthi, 2022; Priya *et al*., 2025).

Public-private partnerships and policy support

Supportive national and international policies are needed to encourage innovation and make it easier for technology developers to enter the precision agriculture (PA) market for medicinal and aromatic plants (MAPs). Collaboration between the public and private sectors can help fund pilot projects, promote research, and expand successful approaches. Practical policy measures such as tax relief, targeted programs for precision MAP farming, and subsidies for digital inputs can further promote the widespread use of these technologies in agricultural production sectors (Hasan *et al*., 2023; Khaspuria *et al*., 2024).

Conclusions and Recommendations

Application of precision agriculture is limited in medicinal and aromatic plant production, although its significance is well recognized. Key obstacles include higher initial costs, limited computer literacy, poor infrastructure, and no attractive schemes for growers, particularly small landholders. Apart from these obstacles, the main issue is that these AI tools are site- and species-specific, and cannot be customized by growers according to their needs and crops. Recently, however, several practical solutions have emerged, including affordable sensors, mobile-based advisory tools, and blockchain systems that enable product traceability. These innovations can make precision farming more accessible and cost-effective, especially for small and medium producers seeking to improve efficiency and profitability. Progress will depend on close collaboration between researchers, policymakers, and farmers to address the existing gaps and create supportive frameworks. With the right institutional and technical backing, precision agriculture could substantially raise yields, improve quality, and help MAP growers to meet the international standards and certification requirements.

Acknowledgments

The authors are grateful to the Department of Horticulture Science, Agricultural College, the University of Al-Qadisiyah, Iraq for guiding the research process.

Novelty Statement

This is the first study by using the smart agriculture in improving medicinal and aromatic plant production.

Author's Contribution

Ali Sabah Alhasan: Carried out the literature collection and drafted the manuscript.
Hayder Abbas Drebee, Osama Majeed Hilal, Alaa Taima and Dhafer Alhajim: Participated and carried out the table and figure preparation.
Dalal Tareq Al-Ameri: Conceived the idea and critical review of the manuscript.
Ali Fadaam Almehemdi, Raad Farhan Shahad, Hayyawi WA Al-Juthery and Raid Shaalan Jarallah: Participated and improved the manuscript.
All authors read and approved the final manuscript.

Generative AI and AI-assisted technology statement

The authors declare that no generative AI and AI assisted technology was used in the creation of this manuscript.

Conflict of interest

The authors have declared no conflict of interest.

References

Ahmadi, F., M. Lackner and A. Starzinger. 2025. Challenges encountered in growing medicinal and aromatic plants. In: Medicinal and Aromatic Plants: Pharmaceutical, Food, and Cosmetic Applications, pp. 119-154. https://doi.org/10.1515/9783111469713-003

Ahmed, K.S., M.Z. Majeed, U. Farooq, K. Fatima, H. Aitzaz, M. Abbas and M.A. Riaz. 2025. Botanical pesticidal products in the world and in Pakistan: A comparative review. Sarhad J. Agric., 41(1): 408–415. https://doi.org/10.17582/journal.sja/2025/41.1.408.415

Alam, A., S. Rizvi and R. Shaikh. 2021a. Image-based deep learning method for early disease detection in Withania somnifera. Plant Pathol. J., 20(3): 145–152.

Alam, A., S.K. Yadav and R. Verma. 2021b. Role of precision pesticide delivery in medicinal

plant cultivation: A case study of *Cymbopogon flexuosus*. J. Med. Plant Res., 15(7): 155–160.
Alami, M.M., S. Guo, Z. Mei, G. Yang and X. Wang. 2024. Environmental factors on secondary metabolism in medicinal plants: Exploring accelerating factors. Med. Plant Biol., 3(1). https://doi.org/10.48130/mpb-0024-0016
Arenas-Salazar, A.P., M. Schoor, B. Parra-Pacheco, J.F. García-Trejo, I. Torres-Pacheco and A.A. Feregrino-Pérez. 2024. Intercropping systems to modify bioactive compounds and nutrient profiles in plants: Do we have enough information to take this as a strategy to improve food quality? A review. Plant., 13(2): 194. https://doi.org/10.3390/plants13020194
Aulakh, R. and A.K. Malhi. 2021. Challenges and opportunities in medicinal plant farming: A review. J. Med. Plants Stud., 9(2): 14–18. https://doi.org/10.22271/plants.2021.v9.i3a.1275
Bahuguna, S., S. Anchal, D. Guleria, M. Devi, Meenakshi, D. Kumar and A. Kumar. 2022. Unmanned aerial vehicle-based multispectral remote sensing for commercially important aromatic crops in India for its efficient monitoring and management. J. Indian Soc. Remote Sens., 50(2): 397–407. https://doi.org/10.1007/s12524-020-01302-5
Bakhshi, D., M. Naderidarbaghshahi and M. Ghasemi. 2022. Improving water-use efficiency and essential oil content in *Rosa damascena* using UAV-based thermal imaging. J. Essent. Oil Res., 34(1): 35–44.
Benitez, F., P. Morais and A. Dias. 2023. Robotic harvesting systems for Aloe cultivation: Performance and economic evaluation. J. Precis. Mech. Agric., 9(1): 51–60.
Bhatnagar, S., R. Mishra and V. Saini. 2022. Optimizing essential oil content in *Ocimum basilicum* using support vector machines. Hortic. Inform., 11(1): 58–65.
Binyam, G., T. Alemayehu and M. Gashaw. 2022. Low-cost sensor-based irrigation for MAPs in Ethiopia's drylands. Afr. J. Smart Farm., 4(1): 56–64.
Chakrabarti, D., S. Sengupta and A. Roy. 2022. Digital traceability tools in MAP supply chains: Potential and limitations. Med. Plant Ind. Rev., 4(3): 101–110.
Chen, X. 2025. The role of modern agricultural technologies in improving agricultural productivity and land use efficiency. Front. Plant Sci., 16: 1675657. https://doi.org/10.3389/fpls.2025.1675657
Chopra, A., A. Yadav and R. Tyagi. 2021. Precision agrochemical application and residue control in medicinal crops: A field approach. J. Agroecol. Sus tain. Syst., 45(3): 275–282.
Choudhary, K. and P. Das. 2023. Automated disease monitoring in *Withania somnifera*: A precision path to higher alkaloid yield. Ind. J. Precis. Hortic., 2(2): 89–96.
Dajic-Stevanovic, Z. and D. Pljevljakusic. 2015. Challenges and decision making in cultivation of medicinal and aromatic plants. In: Medicinal and Aromatic Plants of the World: Scientific, Production, Commercial and Utilization Aspects. Springer Netherlands, Dordrecht, pp. 145–164. https://doi.org/10.1007/978-94-017-9810-5_8
Das, S., H.K. Patra and P. Mishra. 2022. Optimizing water use in aromatic grasses using variable rate irrigation. J. Appl. Hortic., 24(1): 60–65.
aromatic MAPs of Indo-Gangetic plains. J. Precis. Hortic., 14(1): 51–59.
El Fadili, A., H. Bennani and S. Lachheb. 2021. Remote sensing for saffron yield improvement in Moroccan highlands. Afr. J. Agric. Res., 16(7): 1024–1033.
Figueroa, N., R. Vargas and F. Montoya. 2022. Development barriers for precision agriculture in specialty crops. Agric. Syst., 196: 103333.
Gebbers, R. and V.I. Adamchuk. 2010. Precision agriculture and food security. Sci., 327(5967): 828–831. https://doi.org/10.1126/science.1183899
Getahun, S., H. Kefale and Y. Gelaye. 2024. Application of precision agriculture technologies for sustainable crop production and environmental sustainability: A systematic review. Sci. World J., 2024(1): 2126734. https://doi.org/10.1155/2024/2126734
Gulati, B., Z. Zubair, A. Sinha, N. Sinha, N. Prasad and M. Semwal. 2025. Predicting nitrogen flavanol index (NFI) in *Mentha arvensis* using UAV imaging and machine learning techniques for sustainable agriculture. Drones, 9(7): 483. https://doi.org/10.3390/drones9070483
Gupta, R. and S. Rao. 2021. Robotic harvesting technology for Aloe vera: Efficiency, quality, and scale-up potential. Adv. Agric. Robot., 12(2): 99–107.

Gupta, S. and A. Awasthi. 2022. Precision agriculture capacity development in Indian medicinal plant extension systems. J. Agric. Train. Educ., 18(2): 121–129.

Gurusamy, U., V. Sangeetha, G. PraveenKumar and A. Meenakshi. 2025. Impact of blockchain technology in agriculture supply chain: A comprehensive review of applications, challenges, and future directions. J. Sustain. Compet. Intell., 15: e0519. https://doi.org/10.37497/eagleSustainable.v15i.519

Hasan, M., F. Sultana and A. Karim. 2023. Policy frameworks for digital farming integration in herbal agriculture. J. Agric. Dev. Policy, 6(1): 43–51.

Hernández-Bolaños, E., V. Sanchez-Retuerta, L. Matías-Hernández and L. Cuyas. 2025. Promising applications on the use of medicinal and aromatic plants in agriculture. Disc. Agric., 3(1): 36. https://doi.org/10.1007/s44279-025-00187-7

Jampílek, J. and K. Kráľová. 2023. Impact of abiotic stresses on production of secondary metabolites in medicinal and aromatic plants. In: New Frontiers in Plant-Environment Interactions: Innovative Technologies and Developments. Springer Nature Switzerland, Cham, pp. 169–252. https://doi.org/10.1007/978-3-031-43729-8_8

Jamwal, R., P.S. Ahuja and R. Kaur. 2023. Traceability challenges in MAP certification systems and role of precision agriculture. Med. Plant Certif. J., 3(1): 27–34.

Jawad, M.K., S.A. Al-Fatlawi and J.A. Al-Jumaili. 2022. Role of artificial intelligence in precision agriculture: A review. Mater. Today Proc., 56(5): 2417–2421.

Joseph, A. and B. Chatterjee. 2023. Blockchain and AI integration for MAP supply chain authentication: A case of Aloe vera. J. Herbal Prod. Traceability., 2(1): 17–26.

Khaspuria, G., A. Khandelwal, M. Agarwal, M. Bafna, R. Yadav and A. Yadav. 2024. Adoption of precision agriculture technologies among farmers: A comprehensive review. J. Sci. Res. Rep., 30(7): 671–686. https://doi.org/10.9734/jsrr/2024/v30i72180

Kour, K. and S. Rana. 2020. Smart agriculture in medicinal plants cultivation: A potential approach for enhanced productivity. Indian J. Agric. Sci., 90(6): 1085–1092.

Kumar, A., R.K. Yadav and A. Kumar. 2022. Impact of precision fertigation on biomass and withanolide content in *Withania somnifera*. Ind. Crops Prod., 183: 114934.

Kumar, V., R. Anitha and M. Srinivas. 2022a. Adoption of precision irrigation tools in MAP cultivation: A study on lemongrass farmers in South India. Ind.J. Med. Plant Sci., 11(2): 55–63.

Kumar, V., R. Sahu and K. Pathak. 2022b. Role of smart fertigation in optimizing menthol yield from *Mentha arvensis*. Ind. J. Essent. Oil Res., 34(2): 87–94.

Kumar, V., A. Zadokar, P. Kumar, R. Sharma, R. Sharma, M.W. Siddiqui and R. Chandora. 2025. Advancing medicinal plant agriculture: Integrating technology and precision agriculture for sustainability. Peer.J, 13: e19058. https://doi.org/10.7717/peerj.19058

Leung, Y., P. Verhoeven and R. Drechsel. 2023. Precision agriculture and traceability in herbal value chains: Gaps in regulatory harmonization. Med. Plants Trade J., 5(1): 41–49.

Li, C. and M. Wang. 2024. Pest and disease management in agricultural production with artificial intelligence: Innovative applications and development trends. Adv. Resour. Res., 4(3): 381–401.

Lopes, A., M. Oliveira and J. Dias. 2022. Blockchain and IoT in herbal supply chains: A new era for quality control. Plant Prod. Traceability Rev., 5(3): 91–101.

Mahato, D., H. Mahto and S. Kumari. 2025. Medicinal and aromatic plant cultivation and sustainable development. In: *Industrial Crops* Improvement: Biotechnological Approaches for Sustainable Agricultural Development. Springer Nature Switzerland, Cham, pp. 135–153. https://doi.org/10.1007/978-3-031-75937-6_8

Manickam, V.S., P. Rathi and D. Narayanan. 2023. Precision farming and its barriers in medicinal herb production systems of Tamil Nadu. J. Ethnopharm. Stud., 4(2): 90–99.

Marcelino, S., S. Hamdane, P.D. Gaspar and A. Paço. 2023. Sustainable agricultural practices for the production of medicinal and aromatic plants: Evidence and recommendations. Sustainability, 15(19): 14095. https://doi.org/10.3390/su151914095

Markets and Markets. 2022. Essential oils market by product, application and region – Global forecast to 2027. Markets and Markets.

Maryam, G., N. Khan, S. Sehar, Z. Ibrahim, S. Ashraf, S. Areej and M.F. Adil. 2025. Optimizing crop health with artificial intelligence and machine learning technologies. In: Ecologically Mediated Development: Promoting Biodiversity Conservation and Food Security. Springer Nature Singapore, Singapore., pp. 487–509. https://doi.org/10.1007/978-981-96-2413-3_22

Mathenge, M., B.G. Sonneveld and J.E. Broerse. 2022. Application of GIS in agriculture in promoting evidence-informed decision making for improving agriculture sustainability: A systematic review. Sustainability, 14(16): 9974. https://doi.org/10.3390/su14169974

Meena, R.K. and D. Solanki. 2020. Enhancing root biomass and bioactive compound yield in *Withania somnifera* through potassium optimization. Ind. J. Plant Physiol., 25(2): 173–179.

Menon, A., S. Pillai and D. George. 2020. Field testing of a precision transplanter for *Ocimum sanctum*. Agric. Mach. Bull., 7(1): 11–18.

Meriç, M.K. 2025. Implementation of a wireless sensor network for irrigation management in drip irrigation systems. Sci. Rep., 15(1): 14157. https://doi.org/10.1038/s41598-025-97303-w

Mishra, R. and S. Patra. 2023. Traceability and phytochemical consistency in medicinal plants: The role of variable rate application. Ind. Crops Prod., 198: 116760.

Mitra, A., S. Chaudhuri and D. Pal. 2022. Robotic harvesting in medicinal plants: Application and innovation in Aloe vera. J. AgriTech Res., 10(4): 205–212.

Moghadam, S., R. Alimardani, M. Narimani and A. Moghimi. 2026. Internet of Things and artificial intelligence for smart agriculture: A systematic mapping review of sensors, platforms, connectivity and machine learning applications (2014–2024). agriRxiv, 20260010565. https://doi.org/10.31220/agriRxiv.2026.00392

Mohammed, M.E. and M. Munir. 2025. Towards smart farming: Applications of artificial intelligence and Internet of Things in precision agriculture. In: *Hyperautomation in Precision Agriculture*. Academ. Press., pp. 27–37. https://doi.org/10.1016/B978-0-443-24139-0.00003-5

Nayyar, H., S. Sharma and A. Rana. 2021. Mechanized nursery production for medicinal plants: A sustainable approach. Med. Plant Mech. Rev., 3(1): 34–41.

NMPB. 2022. Annual report 2021–2022. National Medicinal Plants Board, Ministry of AYUSH, Government of India.

Olatunji, D., O. Ayodele and M. Sanni. 2023. Data constraints in AI adoption for African medicinal plant production. Afr. J. Smart Agric., 2(2): 88–97.

Panda, B., S. Patnaik and R. Mohapatra. 2023. Development of a real-time decision support system for lemongrass cultivation using IoT and climatic models. Agric. Syst., 210: 103631.

Pandey, A., V. Chaurasiya and A. Tiwari. 2023. Sustainability in medicinal and aromatic plants production: A critical review. Ind. Crops Prod., 201: 116684.

Pandit, V., M. Sravya, C. Ravali, S. Fiaz, A. Tariq and S. Chatterjee. 2026. Precision agriculture in the era of technological advancement. In: *Artificial Intelligence and Data Sciences for Precision Agriculture*. Springer Nature Switzerland, Cham, pp. 159–186. https://doi.org/10.1007/978-3-032-12770-9_8

Patel, H. and R. Jain. 2023. Designing farmer-friendly precision agriculture kits for aromatic plant growers. J. Precis. Agri-Innov., 3(1): 22–31.

Patel, M.A., H.C. Chauhan and K.M. Patel. 2021. Precision farming tools in medicinal plant production: Scope and applicability. J. Appl. Nat. Sci., 13(1): 134–139.

Pereira, M., J. Ramos and H. Silva. 2022. Site-specific herbicide application in rosemary: Effects on weed control and residue management. Hortic. Technol. Bull., 13(4): 205–213.

Pineda, M., M. Barón and M.L. Pérez-Bueno. 2020. Thermal imaging for plant stress detection and phenotyping. Remote Sens., 13(1): 68. https://doi.org/10.3390/rs13010068

Prasanna, R., P. Saravanan, M. Jenath, G. Saravanan and R. Rajesh Kanna. 2024. IoT based soil moisture monitoring and nutrients suggestion based on the soil pH value. In: Proc. Int. Conf. Power, Energy, Control and Transmission Systems *(ICPECTS)*. IEEE, pp. 1–6. https://doi.org/10.1109/ICPECTS62210.2024.10780246

Priya, N.K., S.S. Patil, S.K. Vishwakarma, D.R.K. Saikanth, I. Mishra, S. Tripathi and S. Shastri. 2025. Digital innovations in extension education: A review of emerging technologies and their impact on agricultural knowledge dissemination. J. Exp. Agric. Int., 47(5): 408–423. https://doi.org/10.9734/jeai/2025/v47i53430

Rana, D., P. Kapoor and S. Kumar. 2022. Remote sensing and spectral analysis of essential oil crops under smart agriculture. Remote Sens. Appl.: Soc. Environ., 25: 100723.

Rathi, N., D. Singh and A. Kumari. 2020. Effect of irrigation and nitrogen on menthol yield in *Mentha arvensis* under semi-arid conditions. Agric. Res., 9(4): 528–534.

Rathod, P., S. Sharma and B. Mehta. 2021. ICT constraints in horticulture-based decision tools among medicinal crop growers in UP. Asian J. Ext. Educ., 39(1): 25–32.

Raut, D. and N. Mishra. 2021. Use of spectral imaging for early detection of foliar blight in *Withania somnifera*. J. Med. Crop Diagn., 8(2): 69–75.

Ricci, A., M.L. Grilli and L. Neri. 2020. Precision fertigation and drone-assisted harvesting in Mediterranean MAPs. Ital. J. Agron., 15(3): 219–228.

Saleem, S.R., Q.U. Zaman, A.W. Schumann and S.M.Z.A. Naqvi. 2023. Variable rate technologies: Development, adaptation and opportunities in agriculture. In: *Precision Agriculture*. Academ. Press., pp. 103–122. https://doi.org/10.1016/B978-0-443-18953-1.00010-6

Saxena, M., D. Sharma and R. Joshi. 2021. Agronomic interventions for enhancing essential oil composition in *Ocimum basilicum*. J. Essent. Oil Bear. Plants., 24(2): 300–307.

Sharma, R., H. Singh and B. Dhillon. 2023. Precision agriculture: A pathway for sustainable and climate-resilient horticulture. Agric. Rev., 44(1): 1–12. https://doi.org/10.5958/2582-2527.2023.00001.5

Shrestha, D., N. Gurung and P. Lama. 2022. Adoption potential of PA among MAP cooperatives in Nepal: A socio-economic analysis. Int. J. Herbal Agron., 5(2): 61–70.

Silva, T., R. Andrade and M. Costa. 2021. Application of multispectral imaging to optimize basil cultivation under variable nitrogen regimes. Braz. J. Agric. Imaging., 11(3): 163–172.

Singh, A., S. Kumari and V. Gupta. 2021. Challenges in cultivation and conservation of medicinal plants in India. Curr. Bot., 12: 16–22.

Singh, R., A. Chauhan and N. Gupta. 2023. Machine learning approaches for yield and oil content prediction in aromatic crops. Comput. Agric., 7(2): 112–120.

Singh, P., S.L. Nayak, R. Sharkar, A. Sarkar, S. Dutta and D. Paul. 2025. Application of modern techniques in cultivation of medicinal plants: A review. Plant Arch., 25: 1947–1962.

Singh, S., V.P. Singh, R.C. Nainwal, D. Singh and S.K. Tewari. 2024. Cultivation of medicinal and aromatic plants for specialty industrial materials. In: Medicinal and Aromatic Plants: Current Research Status, Value-Addition to Their Waste, and Agro-Industrial Potential, Vol. II. Springer Nature Switzerland, Cham, pp. 231–241. https://doi.org/10.1007/978-3-031-64601-0_16

Tadesse, M., G. Hailu and T. Kassa. 2022. Limitations of digital farming tools in Ethiopia's aromatic crop sector. East Afr. J. Agric. Technol., 8(4): 115–123.

Tariq, H., A. Bashir and A. Zaman. 2022. Knowledge gaps and training needs for precision agriculture adoption in medicinal plant farming in Pakistan. Pak. J. Agric. Ext., 36(1): 39–46.

Tiwari, S., R. Kaur and P. Verma. 2022. AI-based image classification for foliar disease detection in *Withania somnifera*. J. Med. Plant Stud., 10(4): 88–94.

Tiwari, V. and R. Joshi. 2023. Smart irrigation and its impact on essential oil composition in lavender. J. Aromat. Crop Sci., 7(1): 29–36.

Varghese, R., H. Shringi, T. Efferth and S. Ramamoorthy. 2025. Artificial intelligence driven approaches in phytochemical research: Trends and prospects. Phytochem. Rev., 1–16. https://doi.org/10.1007/s11101-025-10096-8

WHO. 2023. WHO traditional medicine strategy 2023–2032. World Health Organization, Geneva.

Yadav, V., R. Singh and H. Kaur. 2021. Spatial nitrogen variability and its influence on essential oil yield in *Mentha piperita*. Plant Arch., 21(2): 496–502.

Yousefzadeh, H., M. Zarei, F. Esfandiari *et al.* 2022.

Agronomic practices and environmental factors influencing secondary metabolite production in medicinal plants: A comprehensive review. Ind. Crops Prod., 178: 114627.

Zamani, S., M. Fathi, M.T. Ebadi and Á. Máthé. 2025. Global trade of medicinal and aromatic plants: A review. J. Agric. Food Res., 101910. https://doi.org/10.1016/j.jafr.2025.101910

Zhang, T., L. Wei and X. Luo. 2023. Greenhouse decision systems for quality enhancement of *Panax notoginseng* in Yunnan. J. Chin. Med. Agric., 10(1): 29–38.

Zhong, L., X. Wu, R. Ding, C. Wang, L. Li, J. Zhang and S. Zhong. 2025. Perspectives on the application of remote sensing technology in the cultivation of medicinal plants. Int. J. Remote Sens., 46(5): 2055–2088. https://doi.org/10.1080/01431161.2024.2443620

Zhou, L., X. Ma, X. Zhao and Y. Xu. 2023. Role of IoT and AI in precision agriculture: A review on recent developments. Comput. Electron. Agric., 205: 107611.