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APPLICATION OF MODERN TECHNIQUES IN CULTIVATION OF MEDICINAL PLANTS: A REVIEW

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ABSTRACT

The increase in global health concerns has spurred a growing interest in preventive medicine. This involves utilizing herbal remedies known for their proven benefits and minimal side effects. These natural remedies are widely utilized particularly amid rising geriatric and lifestyle diseases. However, this increased demand has led to overexploitation and unregulated harvesting of medicinal plants. Shockingly, over 80% of medicinal plants are collected from the wild in a destructive manner, jeopardizing the sustainability of numerous species that have now become rare, endangered, or threatened. This unsustainable practice significantly impacts their natural populations and survival rates. To counter this, there is a growing necessity for sustainable cultivation due to the depletion of wild resources. Sustainable cultivation integrates traditional wisdom, scientific advancements, and community involvement while adhering to ethical and regulatory standards. Establishing successful farming models requires identifying optimal crops through GIS-based agro-ecological studies. This involves assessing climatic suitability and historical Good Agricultural Practices (GAP). Aligning with this, methods such as organic cultivation and advancements in genetics and biotechnology notably improve medicinal plant quality and yield.

***Keywords* :** Medicinal plants, Biochar, Bioformulations, Good Agricultural Practices, Organic farming

Introduction

The rich tradition of using medicinal plants extends across various nations, serving diverse purposes from medicinal remedies to cosmetic formulations. The Asia-Pacific region, especially India and China, boasts extensive diversity in medicinal plants. India alone harbors over 8000 medicinal plant species, with 2500 used in traditional medicine, are predominantly found in regions like Uttaranchal, Sikkim, and North Bengal (Vijayan *et al.*, 2017). The global herbal market is projected to grow significantly, with India and China leading as major exporters (Jadhav *et al.* 2020). However, the increased demand has led to over-harvesting of these plants in the wild, endangering their existence and the livelihoods of farmers and communities (Sundarrajan and Bhagtaney, 2024). Since the medicinal plants form an important health commodity, it is imperative to urgently address the need for the sustainable use and conservation of this valuable bio-resource. Efforts are underway globally to protect natural resources, with a focus on encouraging cultivation rather than wild harvesting. Furthermore, the quality aspects are the most important and should be taken care from raw material stage to finished product. Stringent rejection of batches occurs due to high pesticide and heavy metal residues in medicinal plants. Hence, there is a notable shift from inorganic fertilizers and pesticides toward safer alternatives like bioformulations and botanicals for disease and pest control, aligning with a preference for organic cultivation. Ensuring stringent agricultural practices from inception to completion is essential for upholding the quality of herbal products. Leveraging GIS and remote sensing techniques facilitates precise site-specific cultivation of medicinal herbs. Moreover, incorporating genetics and biotechnological tools into the cultivation of medicinal plants guarantees the attainment of superior yields. These approaches are extensively explored across various sections and subcategories.

Application of remote sensing and geographic information system (GIS)

The major function for which remote sensing and GIS is applied in cultivation of medicinal plants is identification of area and conservation of threatened species important for drugs synthesis. GPS and GIS technologies significantly enhance precision agriculture by offering precise location data and spatial analysis capabilities. GPS enables accurate navigation, optimizing field operations, while GIS supports the implementation of variable rate technology (VRT), allowing adjustments in input application according to field variability. GPS-based applications find utility in agriculture planning, field mapping, soil analysis, crop scouting, variable rate application, and yield mapping, contributing to more efficient and sustainable farming practices (Balyan *et al.* 2024). Remote sensing and GIS software such as ArcGIS, ERDAS, IMAGINE, ENVI, Geomatica, GeoMedia, ILWIS, and ER Mapper are utilized for studying crops and crop modeling (Koshal, 2010). These software tools enable researchers and practitioners to analyze and interpret remote sensing data, perform spatial analysis, and develop crop models to better understand various aspects of crop growth and development. These technologies are invaluable for research and development in the production, protection, development, and management of medicinal crops at local, regional, and global scales.

The type, distribution, and application of medicinal plants is constantly changing in the world, so it has become important to identify the type and distribution of medicinal plants in real time accurately and quickly in order to further determine the development policy of related industries and protect the vulnerable genotypes. At the same time, medicinal plants have many diverse species, diverse habitats, and dispersed growth distribution, which make research problems more complex. Traditional surveys of medicinal plants mainly include field surveys, historical data collection, which are greatly influenced by subjective factors, complicated, and lack scientific rigor. Therefore, identification of different medicinal plants, and accurate spatial distribution, aided by remote sensing technology is of great significance for their protection and utilization. Meng *et al.* (2023) were able to identify, classify and extract information about Chinese Medicinal Plants (CMPs). GIS complements remote sensing by providing a spatial framework for integrating, analyzing, and visualizing complex geospatial data related to medicinal plants. By incorporating environmental variables, such as soil types, elevation, and climate, GIS enables the creation of predictive models for plant distribution and abundance. Such integrative approaches enhance our understanding of the ecological requirements of medicinal plants, aiding in sustainable harvesting practices and the identification of potential cultivation sites by taking into account their climatological characters for successful cultivation (Singh *et al.* 2022). Al-Bakri *et al.* (2011) integrated GIS and ground surveys to medicinal plants in a semi-arid and arid region in the north-west of Jordan. In Agra, Biswas and Varun (2017) identified 56 plant species from 33 families, mapping their distribution using GPS locations in a GIS environment. Subsequently, this information was shared on a Web GIS platform via ArcGIS Online, creating a dynamic, user-friendly application for easy reference and utilization by others. The synergy between remote sensing and GIS not only facilitates the assessment of the current status of medicinal plant populations but also supports long-term monitoring and conservation efforts, ensuring the sustainable utilization of these valuable resources. Numerous studies have successfully employed these technologies in the field of medicinal plant research, enhancing our knowledge of plant ecology and contributing to the development of effective conservation strategies.

Good Agricultural Practices (GAP)

Cultivating medicinal plants while maintaining consistent quality is a significant challenge due to various biological and environmental factors (Bansal *et al.* 2016). Good Agricultural Practices (GAP) for medicinal plants are pivotal, focusing on sustainable farming methods and ensuring safe, healthy, and economically viable produce while addressing social and environmental responsibilities (Saha *et al.*, 2018; FAO, 2003). The World Health Organization (WHO) initiated the GAP guidelines for herbal medicines, emphasizing quality control and safety (Saha *et al.*, 2018). These guidelines complement Good Manufacturing Practices (GMP) are fundamental in maintaining the quality of the final medicinal product. Good agricultural practice starts from identification of the right species and its profiling. Utilizing healthy planting material serves as the cornerstone for ensuring a safe and robust harvest. Agronomic strategies encompassing the utilization of fertile soil, appropriate inputs, cultural methodologies, and meticulous harvesting techniques are vital. Emphasizing sanitation both in the field and among personnel is paramount in adhering to Good Agricultural Practices (GAPs). Additionally, postharvest processing stands as an indispensable component within the GAP protocol, ensuring the production of high-quality final products. In India, where a vast majority of traditional medicinal formulations rely on plant-based raw materials, the National Medicinal Plants Board (NMPB) developed GACP guidelines emphasizing biodiversity conservation and stringent collection practices (National Medicinal Plant Board, 2009). The process begins by identifying the correct species and using healthy planting materials for a secure harvest. Agronomic practices within GAP, including soil management and precise harvesting methods, aim to maximize yield potential (Fig.1). Sanitation standards, vital for preserving produce quality, are rigorously upheld in both field and personnel care. Postharvest processing, an integral part of GAP, ensures the creation of high-quality end products.

Fig. 1 : Basic components of GAP

Pre-cultivation phase

The quality of seeds used in cultivating medicinal plants significantly impacts the final product. Insufficient authentication and poor-quality seeds often lead to compromised productivity and affect the active constituents and overall quality of the herbal produce. Wangchuk *et al.* (2011) highlight the importance of proper authentication through taxonomical identity, phenotype/genotype, and breeding history. Selection of the cultivation site also plays a crucial role. Meteorological and toxicity indicators should inform this decision, with an analysis of rainfall, temperature, and other climate data over a few years to assess crop suitability. Imbalanced climatic conditions can stress plants, reducing their productivity and making them more vulnerable to diseases, pests, and toxicity indicators (Kosalec *et al.*, 2009). Addressing toxicity concerns through phyto-remediation techniques, as suggested by Jadia and Fulekar (2009), can help control the impact of toxicity indicators on crops. Additionally, the availability of high-quality water is essential for proper plant growth, as poor water quality can lead to nutritional deficiencies and impact uptake of essential elements like potassium and calcium (Baligar *et al.*, 2001). Different water types used for irrigation, such as saline or acidic water, can negatively affect crop growth by impeding soil permeability, root growth, and nutrient uptake. This can result in various issues like waterlogging, toxicity due to high salt levels, and anatomical adverse effects in plants (Hamdy, 1993). Soil pH and texture are crucial factors influencing soil micro-organisms, which in turn impact productivity. Excessive use of nitrogen fertilizers can alter soil pH, leading to either acidity or alkalinity, affecting plant growth and quality (Liao *et al.*, 2021). These considerations collectively underscore the importance of a comprehensive approach to cultivation that addresses various environmental and soil factors for optimal medicinal plant growth and quality.

Cultivation phase

Sowing involves critical aspects like plant spacing, seeds per acre, depth, timing, and method. Maintaining optimal distances between seeds and rows is crucial for factors such as crop growth, root density, height, leaf count, biomass, and active constituents, impacting crop quality (Ngullie and Biswas, 2017). It is recommended to validate suitable techniques for cultivating medicinal plants commercially. Fertilization should meet national/international standards, minimizing pesticide residue and toxicity. Organic pesticides or fertilizers, applied by qualified personnel, are advisable (Abhilash and Singh, 2009). Other than this, irrigation management is also needs proper attention as it directly affects yield as well as quality of the produce. There are several agronomic interventions which is crucial during cultivation phase to ensure a good harvest (Table 1)

Table 1 : Agronomic interventions during cultivation phase as a part of GAP

Agronomic interventions	Name of the crop	Management practice	Reference
Improved seeding/ planting techniques	*Chlorophytum borivilianum*	Planting on raised bed during the month of June-July with a seed rate of 600-700 kg/ha	Singh *et al.*, 2003
	Ocimum sangtum	Sowing at a depth of 0.3-0.6 cm maintaining a spacing of 10-15 cm between rows	Makri and Kintzios, 2008
	Salvia hispanica	Direct seeding with a spacing of 55 cm X 25 cm during rabi season	Kundu *et al.*, 2023
Improved nutrient management	*Ocimum sangtum*	Incorporation of cluster bean residue prior to transplanting and application of 100% RDN through FYM +microbial consortia	Smitha *et al.*, 2019
	Andrographis paniculata	Soil application of vermi compost coupled with root dipping in microbial consortium and later, foliar spray of jivamrut at critical growth stages.	Basak *et al.*, 2019
Improved irrigation management	*Aloe barbadensis*	Planting of 60 days old offsets on raised bed along with maintaining 20% available soil moisture throughout cropping period	Singh *et al.*, 2021
	Cassia obtusifolia	Imposing weak drought stress viz. soil moisture at 70% FC can be an effective practical strategy to maximize anthraquinone active constituent yield	Xue *et al.*, 2018

Harvest/post-harvest phase

The best harvest time for medicinal plants coincides with their peak active constituents (Badi *et al.*, 2004). Farmers typically rely on physical cues for harvesting, harvest must be avoided during rainfall and high humidity to prevent moisture in the finished crop. Furthermore, heightened emphasis should be placed on maintaining the cleanliness of harvesters, as neglect in this area can lead to microbial contamination of the produce. Post-harvest handling, crucial for preserving medicinal plant quality, varies by plant type. For instance, Aloe vera requires immediate processing for maximum therapeutic potential (Ahlawat and Khatkar, 2011). Drying, an expensive process, demands temperatures of 30-50°C to safeguard sensitive constituents (Martynenko and Kundra, 2015). Open sunlight drying is not advised due to volatile oil loss; alternatives like solar or freeze drying are preferable. Proper storage is key to maintain potency and efficacy; storage time should not exceed a year for dried medicinal plants (Lisboa *et al.*, 2018). Storage spaces must be clean, rodent-free, with controlled environmental conditions to prevent moisture, microbial and aflatoxin contamination (Khan *et al.*, 2006).

Quality control and testing

Testing soil, water, and harvested plant material for purity, potency, and contaminants ensures high-quality medicinal products. Compliance with local and global regulations throughout cultivation, harvesting, and sales ensures legality, safety, and ethical practices. Quality testing certifies plants for potency, purity, and absence of contaminants, potentially enhancing market value with certifications like organic or Good Agricultural Practices (GAP).

Crop diversification through medicinal plants

Crop diversification holds paramount importance in modern agricultural practices due to its multifaceted benefits like mitigating monoculture associated risks viz. susceptibility to pests, diseases, and adverse weather conditions; enhancing soil fertility and health; promoting biodiversity and ecosystem resilience along with enhanced market opportunities and economic resilience for farmers. Medicinal plants are an ideal candidate that can be used as an important diversification option in various existing monoculture-based systems (Deshpande *et al.*, 2006; Singh *et al.*, 2021). Rice-Wheat cropping system is the most important system of intensively cultivated lands of Punjab, causing a considerable threat to the sustainability of that region. Several medicinal plants like *Phyllanthus embilica*, *Curcuma Longa*, *Aloe vera*, *Ocimum sanctum* have been identified as a potential and economical crop for diversifying the existing system of that region (Kaur *et al.*, 2018). Similarly, more such intensive system can be identified across different agro-climatic zones and included under location specific crop diversification approach involving medicinal plants. Table 2 suggests different recommended diversification options involving medicinal plants across various agro-climatic zones of India (Singh *et al.*, 2021).

Table 2 : Suggested medicinal crops for promotion of crop diversification across different agro-climatic zones

Agro-climatic zone	Recommended diversification options
North-eastern region	*Tagetes minuta, Pelargonium graveolens, Acorus calamus, Hedychium spicatum, Artemisia annua*
Northern region	*Cymbopogon flexuosus, Matricaria chamomilla, Ocimum sp, Tagetes minuta, Rosa × damascena*
Western region	*Cymbopogon flexuosus, Pelargonium graveolens, Pogostemon cablin*
Trans Himalaya	*Artemisia maritima, Lavandula officinalis, Dracocephalum heterophyllum, Valeriana jatamansi*
Coastal and Deccan peninsula	*Cymbopogon martini, Pelargonium graveolens, Pogostemon cablin*
Semi–arid	*Cymbopogon flexuosus, Cymbopogon martini, Pelargonium graveolens*

Organic cultivation practices

Organic products have gained immense popularity worldwide, leading to a significant surge in organic food production. Organic agriculture has emerged as a preferred method for cultivating organic products, including medicinal plants, due to soaring global demand. It mitigates the bioenvironmental sustainability issues caused by indiscriminate use of chemical fertilizers and pesticides in conventional farming. It fosters soil health by boosting organic carbon, phosphorus content, and microbial activity, thereby ensuring sustainable organic crop production. In organic medicinal plant cultivation, various organic amendments effectively meet the crop's nutrient requirements. Weed control primarily relies on cultural, mechanical, and thermal methods, maintaining soil health without the use of synthetic herbicides. While pests pose minimal threats in organic systems due to robust plant health from balanced nutrition and fertile soil. The use of bio pesticides containing natural organism aids in controlling certain pests and diseases. Adoption of organic management practices by farmers not only improves soil quality but also safeguards its productive capacity for future generations (Pinto *et al*. 2023). It underscores the technical aspects of organic farming for medicinal plants, emphasizing its modern, eco-friendly approach. Ultimately, these practices contribute to better economic outcomes in the agricultural sector.

Use of compost on medicinal plants

Composting is a natural process whereby organic biodegradable waste is transformed into a nutrient-rich material known as compost, which serves as a soil conditioner and organic fertilizer (Popkin, 1995). Additionally, composts are utilized to provide biological control against various plant pathogens (Hoitink and Grebus, 1994), with aqueous extracts of compost being proposed as substitutes for synthetic fungicides (Zhang *et al*., 1998). The incorporation of municipal solid waste compost into agricultural soils yields positive effects on crop growth and yield by enhancing soil physical and biological properties (Zheljazkov and Warman, 2004). Numerous studies have explored the application of compost to enhance soil structure, fertility, and subsequently, the development and productivity of medicinal plants. For instance, in Sweet Marjoram (*Majorana hortensis*), soil treated with 15% and 30% aqueous compost extracts exhibited increased essential oil percentage, plant yield, and biomass (Fatma *et al*., 2008). Similarly, investigations on chamomile (*Matricaria chamomilla* L.) revealed that compost treatments, in combination with liquid compost, outperformed chemical fertilizers, resulting in improved growth characteristics of flower heads and essential oil content (Hendawy and Khalid, 2011).

Vermicompost, a nutrient-rich organic fertilizer, offers plant-available nitrates, phosphates, and essential elements like calcium and potassium in forms readily absorbed by plants (Edwards, 1998). Its extensive surface area fosters microbial activity, housing diverse populations of fungi, bacteria, and actinomycetes, while also containing growth regulators that positively impact plant growth (Atiyeh *et al*., 2002). Studies indicate that vermicompost production by earthworms generates cytokinins and auxins, plant hormones that enhance growth (Krishnamoorthy and Vajrabhiah, 1986). Additionally, its high content of humic substances mimics the effects of growth regulators, aiding in plant development (Muscolo *et al*., 1999). The nutrients in vermicompost, such as nitrates, phosphates, calcium, and potassium, significantly boost plant growth and crop yield (Edwards, 1998). Research has shown that vermicompost enhances plant dry weight and nitrogen uptake efficiency (Edwards, 1995; Tomati, 1994), benefiting horticultural and agronomical crops alike (Roy *et al*., 2002). Studies on chamomile production reveal that vermicompost not only stimulates growth and flower yield but also enhances essential oil content (Haj SeyedHadi *et al*., 2011). The rich macro and microelement content in vermicompost significantly contributes to the improved quality and quantity of various crop yields (Roy *et al*., 2002). Specifically, in chamomile cultivation, vermicompost has been found to positively influence essential oil and chamazulene contents (Azizi *et al*., 2009).

Intercropping

Integrating medicinal and aromatic plants (MAPs) into intercropping systems is a promising strategy to boost agricultural income. This method involves growing multiple compatible crops together, diversifying revenue streams and reducing the risk of crop failure. It not only enhances economic returns but also improves soil health. A field experiment was carried out at the research farm of the Central Institute of Medicinal and Aromatic Plants, Lucknow growing mint with radish in a 1:1 ratio, alongside separate crops of mint or radish for comparison. Interestingly, when radish was grown alongside mint, it didn't affect the mint's yield. The combined crops produced 27 tons per hectare of fresh radish, valued at Rs. 54,000 per hectare, showing excellent land use efficiency (Singh *et al*., 2012). Notably, *Withania somnifera* performed exceptionally well when intercropped with peaches, surpassing *Ocimum sanctum* and *Andrographis paniculata*. This suggests that integrating fruit trees with medicinal crops can enhance both productivity and fruit quality (Tripathi *et al*., 2019). In another study, evaluating herbal plants in 36-year-old coconut garden, researchers found that *Alpina galanga*, *Aloe vera*, *Ocimum sanctum*, *Symbopogan flexuosus*, and *Pogestemon cablin* all thrived best as intercrops. These plants not only performed well but also showed economic promise. This indicates that coconut farmers have various options to choose based on market demand and soil suitability, allowing them to earn extra income from their coconut gardens (Mohandas, 2011).

Similarly, in the north Indian plains, Ram *et al*. (2012) conducted a field trial to enhance sarpagandha cultivation alongside pigeon pea. Intercropping two rows of sarpagandha with pigeon pea, spaced at 90 cm, resulted in substantial benefits, producing 5.15 tons per hectare of pigeon pea grain, 10.27 tons per hectare of straw and stalk, and an extra 2.56 tons per hectare of dry sarpagandha root yield. Since majority of the medicinal plants are found in forest and also shade tolerant, therefore agroforestry system offers a convenient strategy for promoting their cultivation and conservation. Tripathi *et al*. (2020) studied the impact of organic manures on *Andrographis paniculata*, *Withania somnifera*, and *Ocimum sanctum* within a peach-based agroforestry system. The silvi-medicinal system integrates trees and medicinal plants to yield various products like food, fodder, fiber, and medicinal herbs. Suvera *et al*. (2015) examined intercropping four *Ocimum* species with 2.5-year-old Karanja trees, resulting in a successful silvi-medicinal system. This system, combining Karanja and *Ocimum* spp., surpassed sole cropping with higher fresh herbage and oil yields. Below, some more beneficial intercropping system are being highlighted in terms of land use efficiency (Table 3) and quality (Table 4)

Table 3: Intercropping system improving overall system land use efficiency

Cropping system	% Improve in system land use efficiency
Geranium + blackgram	33
Geranium + cowpea	29
Palmarosa + cowpea	13
Palmarosa + blackgram	15
Citronella+(greengram-sorghum)	40
Citronella+(greengram-groundnut)	43
Citronella+(greengram-finger millet)	45
Citronella+(cowpea-finger millet)	46

*(Prakash Rao *et al*., 2000)

Table 4 : Intercropping of medicinal plants in Coconut improves the quality particulars and system profitability (Nagwekar *et al*.,2013)

Name of the crop	Quality particulars	Sole crop	Intercrop with coconut	Net B:C in intercropping
Shatavari	Shatavarin, Saponins	0.61 mg ml^{-1} 0.37 Rf value	0.85 mg ml^{-1} 0.45 Rf value	2.09
Adulasa	Alkaloid	2.94 mg ml^{-1}	6.56 mg ml^{-1}	1.96
Arrowroot	Sugar	0.67 mg ml^{-1}	0.72 mg ml^{-1}	2.10
Lemon grass	Citral	0.16 mg ml^{-1}	0.14 mg ml^{-1}	2.13
Citronella	Citranol	7.18 mg ml^{-1}	14.18 mg ml^{-1}	1.75
Sole coconut	-	-	-	1.73

Organic mulching

The increasing global population, coupled with climate change and rising temperatures, intensifies pressure on vital resources like water (Thakur*et al.* 2021). Using mulches on soil surfaces has proven effective in reducing evaporation rates, increasing moisture content, altering soil temperature, curbing erosion, suppressing weeds, and transforming soil properties. Understanding the influence of diverse mulches on soil conditions, growth, yield, and quality of herbal plants is crucial. Organic mulches are cost-effective, readily available, and eco-friendly. Cultivating medicinal plants involves embracing tradition and the rediscovery of ancient agricultural practices. Compared to the bare plot (control), organic mulches significantly boosted total plant and leaf fresh yields of basil, surpassing yields from synthetic mulches. Additionally, the use of organic mulches notably reduced soil temperature by 1 to 6°C (Palada *et al.* 2000).In 2014, Kumar *et al.* used, silver oak (*Grevillea robusta*)tree leaf, poplar leaf (*Populus deltoides*), pine needles (*Pinus roxburghii*), along with an unmulched control. The mulched plots for stevia exhibited elevated organic carbon (OC), available phosphorus (P), nitrogen (N), and potassium (K), accompanied by increased bacterial and fungal populations compared to the unmulched areas. Additionally, poplar leaf mulch led to a notably higher content of Rebaudioside-A in the stevia plants. In organic ginger cultivation with local cv. Bhaisey, various traditional bio-mulches were used, including green leaves of *Artemisia vulgaris*, *Chromolaena odorata*, *Eupatorium odoratum*, *Alnus nepalensis*, and mixed leaves. Notably, *Schima wallichii* fresh leaves stood out, resulting in the longest rhizome size (7.25 cm), the highest number of rhizome fingers per plant (39.23), increased ginger yield (208.54 q/ha), a favorable benefit-cost ratio (1:1.80), reduced disease incidence (16.10%), and substantial soil moisture conservation (44.75%) compared to other bio-mulching materials in organic ginger production.

Effect bioformulations and botanicals

Medicinal plant cultivation prioritizes quality over quantity, favoring sustainable agricultural practices that harmonize with nature (Sharifi *et al.*, 2002).The overuse of chemicals by farmers in agro-ecosystems leads to soil degradation, disrupts soil ecology, and raises soil salinity levels, posing health risks (Lyon *et al.*, 1995). Hence, exploring alternative methods to manage pests and diseases is crucial for reducing environmental pollution. Plant extracts have proven more effective than conventional fungicides and microbial agents in combating various pathogens (Bowers and Locke, 2004). Plants produce a vast array of secondary metabolites that protect them from harmful fungi, preventing significant economic losses (Ghosh *et al.*, 2013). Herbal bio-formulations, utilizing plant extracts, are systemic, specific, cost-effective, and environmentally friendly, lacking residual effects (Singh, 1994). These formulations, incorporating suitable elicitors and binders, offer a balanced composition and serve as a promising alternative to chemical fungicides. Natural products have advantages over synthetics due to their non-toxicity, affordability, biodegradability, and widespread availability (Meena *et al.*, 2020). A bioformulation called Paneer whey-based bioformulation (P-WBF) was created using the *Bacillus safensis* NAIMCC-B-02323 strain found in the rhizosphere of *Stevia rebaudiana*. This was done to improve the soil quality, growth, nutrient absorption, and stevioside content of *S. rebaudiana* plants in a field infested with *Alternaria alternata* (Prakash *et al.*, 2022). Studies on medicinal plants have shown positive effects of bacterial inoculation. For instance, mycorrhizal inoculation increased root length and overall plant growth in *Scutellaria integrifolia* in low phosphorous soils (Joshee *et al.*, 2007). Inoculation of Azotobacter in *Rosmarinus officinalis* increased the concentration of plant essence (Leithy *et al.*, 2006). Simultaneous application of mycorrhiza fungus with *Azospirillum* and *Bacillus* increased the biomass of *Cymbopogon maritinii* (Ratti *et al.*, 2001). Bio-fertilizer application also significantly increased the growth of *Thymus vulgaris* (Youssef *et al.*, 2004). The growth improvement in medicinal plants due to bacterial inoculation could be attributed to faster nutrient absorption rates, resulting in increased accumulation of nutrients like nitrogen, phosphorus, and potassium in the leaves (Saharan and Nehra, 2011). Fennel root symbiosis with mycorrhizal fungi notably enhanced various properties, with *Glomus fasiculatum* leading to a significant 78% increase in essential oil concentration (Kapoor *et al.*, 2004).

Chemicals used for disease control can harm the environment and alter medicinal plant properties. To sidestep these risks, natural products from certain plants are employed for disease management (Bhatia and Awasthi, 2007). These plant-derived solutions remain a focus for safe and simple applications against plant pathogens and pests, offering potential for economically superior products. Botanical pesticides have gained attention due to public concerns about synthetic chemicals and the rise in organic farming practices. Beyond their natural origin, botanicals are prized for their limited environmental impact. Evidence supports that phytoextracts can boost plant resistance against various pathogenic fungi (Paul and

Sharma 2002). At a concentration of 10%, neem leaf extract displayed a 58.6% inhibition in radial growth and a 56.5% inhibition in spore germination. Similarly, *Ocimum sanctum* exhibited effectiveness, with a 54.7% inhibition in radial growth and a 50.4% inhibition in spore germination of *Alternaria alternata*, the pathogen responsible for Aloe vera dry rot, when compared to the control group (Anamika and Sobita, 2011).

Application of biochar

The soaring costs and detrimental environmental impact of synthetic fertilizers have spurred a quest for alternative, eco-friendly nutrient sources. To tackle the escalating prices and global demand for chemical fertilizers, the focus has shifted to cost-effective strategies involving recycling waste biomass, animal manures, crop residues, and naturally occurring low-grade minerals (Basak, 2017). Organic agricultural practices frequently use farmyard manure, compost, and the emerging use of biochar as potent soil amendments. Biochar is the result of organic materials undergoing high-temperature burning with restricted oxygen. It is a carbon-rich product formed through pyrolysis, known for its porous structure and extensive surface area. Biochar holds essential nutrients like nitrogen, phosphorus, potassium, magnesium, and calcium, directly enhances soil fertility. As time progresses, biochar undergoes gradual mineralization releasing its nutrient content into the soil (Malabadi *et al*., 2023). These approaches aim not only to retain carbon and nutrients from organic materials but also to address critical sustainability issues in agricultural nutrient management (Purakayastha *et al*., 2019). Heavy metal contamination, notably lead (Pb) and cadmium (Cd) in medicinal plants (MPs), poses health risks and diminishes their productivity. Biochar soil amendments offer a solution by immobilizing these toxic metals, enhancing soil quality, and boosting agricultural yield. Moreover, biochar treatments have shown promise in increasing secondary metabolites and antioxidant properties in *Bacopa monnieri*, *Andrographis paniculata*, and *Withania somnifera* (Nigam *et al*., 2021). Similarly, Basak *et al*. (2021) reported that the application of biochar-mineral-complex (BMC) to deeply weathered acidic soil notably enhanced both the herbage yield and the production of bioactive compounds, specifically sennoside, in senna (*Cassia angustifolia* Vahl.).Ng, Charles *et al*. (2023) found that the application of peanut shell biochar @ 5% concentration resulted in enhanced yield and improved quality of *Pinellia ternata* in both completely decomposed granite (CDG) and lateritic soils. Biochar has been extensively explored for its beneficial effects on various medicinal plants, several of which are outlined in the table below.

Table 5: Biochar used as a sustainable catalyst for organic medicinal plant

Crop	Effect	Reference
Marjoram (*Origanum majorana* L.)	Application of oak wood biochar increased the volatile oil, and amount of carvacrol and thymol in the plant.	Tavali and Ismail Emrah (2022)
Rose-scented geranium (*Pelargonium graveolens*)	The utilization of biochar led to an 11.4% increase in plant dry weight and a 9.4% boost in essential oil content.	Calamai *et al*. (2019)
Erigeron (*Erigeron breviscapus*)	The application of biochar @ 15% concentration alleviated Cd toxicity, resulting in the highest shoot biomass and scutellarin content	Zhang *et al*. (2023)
American ginseng (*Panax quinquefolium* L)	Biochar at 1.8% positively influenced *P. quinquefolium* growth and ginsenoside accumulation and enhancing the rhizosphere soil microbial community.	Yang *et al*. (2022)
Basil (*Ocimum basilicum)*	The addition of black cherry wood biochar at a concentration of 3% resulted in a significant increase of 47% in basil root surface area, 37% in root diameter, and 45% in root volume compared to the control group.	Jabborova *et al*. (2021)
Red Sage (*Salvia miltiorrhiza* Bunge)	When biochar was incorporated, there was a 52.8% decrease in Cd content in the leaves and a 43.6% reduction in the roots of *S. miltiorrhiza* compared to the control group.	Liu *et al*. (2016)

Medicinal plants under agro-forestry system

Introducing medicinal plants under the agro-forestry system can be a sustainable intensification option, which has the potential to flourish under different agro-climatic condition. For example, in taungya system, medicinal plants can be grown under newly established forest plantations. Even if the tree components fully cover the ground, there are several medicinal plants which are shade tolerant, and they can easily grow in shady condition (Rao *et al*.,2004). Agro-forestry system might also have beneficial effect on the quality of medicinal plants. Quinine yield and bark yield was reported to increase in *Cinchona ledgeriana* when grown under shade of *Crotalaria anagyroides* , *Tephrosia candida* and *Alnus nepalensis* compared to under unshaded condition (Nandi and Chatterjee, 1991).Some examples of commercially valuable medicinal plants that can be produced as understory components in agro-forestry systems are given below (Table 6).

Table 6: Suitable medicinal plants under agro-forestry system in different agro ecologies

Name	Parts used	Medicinal use	Location
Aconitum heterophyllum	Rhizomes	Hysteria, throat diseases, astringent	Alpine and sub-alpine Himalayas
Amomum subulatum L	Seed	Stimulant, indigestion, vomiting, rectal diseases	Sub-Himalayan range, Nepal, Bhutan
Chlorophytum borivilianum	Tubers	Male impotency, general weakness	India
Costus speciosus	Leaves, stem, rhizomes	Purgative, depurative and as a tonic	India
Panax ginseng	Roots	Tonic	China, Korea, Japan
Cephaelis ipecacuanha	Roots	Whooping cough, bronchial asthma, amoebic dysentery	Brazil, India, Bangladesh, Indonesia
Rauvolfia serpentina	Roots	Hypertension and certain forms of insanit	Sub-montane zone, India
Cimicifuga racemosa	Roots	Menses related problems	North America
Amomum villosum	Seeds	Gastric and digestive disorders	China

Source: Gupta (1986); Saint-Pierre (1991); Rao *et al*. (1999); Garrett and McGraw (2000); Hill and Buck (2000); Teel and Buck (2002).

Integrated pest and disease management

Medicinal plants play a crucial role in traditional herbal remedies, commonly used through infusions and decoctions in developing and underdeveloped nations (Kumar, 2014). Additionally, these plants are commercially utilized in the production of modern drugs, emphasizing the need to scale up their cultivation while ensuring quality. Pest and disease occurrences during the growth phase significantly impact both the quantity and quality of biomass. Notably, fungal diseases such as wilt, blight, root rot, leaf spots, and anthracnose have adverse effects on the yield and quality of medicinal plants. In terms of insect pests, root-knot nematodes, leaf sap-sucking pests (mealy bugs, thrips, aphids, mites), defoliators (epilachna beetles, leaf rollers/ webbers, grasshoppers), flower bud and flower-feeding pests (gall midges, bud worms, thrips) are common invaders during crop cultivation (Gahukar *et al*. 2018).

The use of chemical pesticides poses a serious threat to human health due to the accumulation of toxic residues, making it unsuitable for medicinal plant production. Therefore, an integrated management approach, incorporating cultural practices, biological control methods, and plant-derived products is crucial for ensuring the production of high-quality medicinal plants. To control insect pest infestation, strategies such as neem-based products (leaf or kernel) in powder or liquid form (Gahukar, 2012), growing trap crops, using sticky traps, pheromone traps, and employing biological control through microbial biopesticides like *Bacillus thuringiensis, Metarhizium anisopliae, Beauveria bassiana*, and *Verticillium lecanii*, as well as predators like *Cryptolaemus montrouzieri*, can be effective. A bio-intensive module, including manures, biofertilizers, chemical fertilizers, botanicals like neem seed kernel extract (NSKE), and microbial biopesticides, has been tailored according to pest management requirements (Senthilkumaran, 2008; Thangavel, 2010). Nematodes pose a significant threat to medicinal plants, causing substantial yield loss. Sharma and Pandey (2009) observed that the application of neem cake in the plantation of ashwagandha and senna effectively reduced the population of root-knot nematodes in the soil. In addition to neem cake, the application of humic acid and biocontrol agents, such as *Trichoderma viride* and

Pseudomonas fluorescens, to the soil, proved effective against root-knot nematodes (Ramakrishnan and Senthilkumar, 2009). Wild marigold (*Tagetes* spp.) has the capability to suppress nematode populations and can be utilized as a trap crop, with subsequent incorporation into the soil due to its high toxicity to nematodes.

Plant Growth-Promoting Rhizobacteria (PGPR) strains are known to induce resistance against multiple pathogens in various crops, including medicinal plants. An Integrated Disease Management (IDM) module, incorporating components such as manure (vermicompost), neem cake, and biocontrol agents like *Pseudomonas fluorescens*, *Trichoderma viride*, and *Bacillus subtilis*, can effectively control the spread of diseases such as fruit rot and anthracnose (Nakkeerran *et al*. 2013).

Application of genetics and biotechnology for medicinal plants

The integration of cutting-edge biotechnological tools into the realm of medicinal plants presents a significant opportunity to enhance our ability to manipulate and improve desirable traits in these plants (Fig.3). Molecular markers, genome sequencing, and targeted genome editing methods form essential components of this advanced biotechnology, offering unparalleled precision and efficiency in crafting medicinal plants with specific secondary metabolite profiles. Techniques like RAD-seq enable a thorough examination of genetic diversity within populations of medicinal plants. A comprehensive understanding of genetic diversity is essential for selecting appropriate breeding pairs, identifying valuable traits, and formulating strategies for the conservation of genetic resources. Revolutionary sequencing technologies have streamlined the rapid and cost-effective sequencing of entire genomes of medicinal plants. Genome sequencing provides a holistic comprehension of the genetic makeup, gene distribution, and regulatory elements, facilitating the identification of candidate genes linked to specific traits. The knowledge of genetics and genome of medicinal plants would allow targeted genome editing with tools like ZFN, TALEN, CRISPR-Cas9 to enhance desired traits, such as increased medicinal compound content, disease resistance, or adaptation to specific environmental conditions (Niazian *et al*., 2018). RNA-seq is a powerful tool for profiling gene expression, aiding in the identification of genes involved in the biosynthesis of secondary metabolites. Understanding the genetic regulation of secondary metabolite production facilitates the targeted enhancement of medicinal compound content. A grasp of plant genetics assists in identifying genes associated with disease resistance and environmental adaptation. This information enables researchers to develop medicinal plants with heightened resilience to diseases and improved adaptability to diverse growing conditions. Genetic insights contribute to the conservation of rare and endangered medicinal plant species by guiding breeding programs focused on preserving genetic diversity. Biotechnological tools play a role in increasing medicinal plant production through the development of high-yielding and disease-resistant varieties.

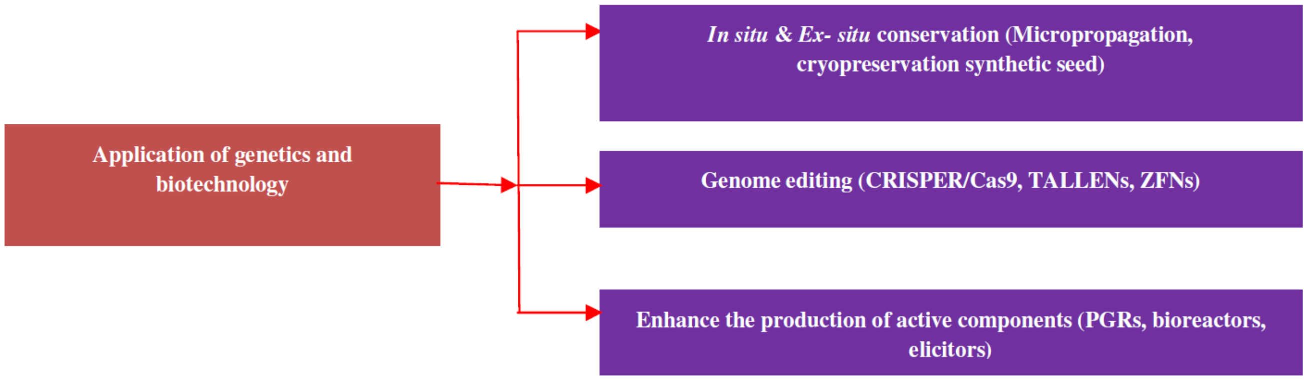

Fig. 2 : Application of genetics and biotechnology in medicinal plants

Medicinal plants are rich source of secondary metabolites which forms the basis or raw materials for pharmaceutical industries. These secondary metabolites when produced in plant system naturally, very low production is received in comparison to the demand from the drug industries. Additionally, these secondary metabolites are specifically generated in distinct plant organs such as leaves, flowers, stems, and roots. Consequently, the extraction and isolation methods employed to obtain a particular secondary metabolite from specific plant tissues play a pivotal role. Thus, meeting the demand for large-scale production of specific secondary metabolites can be accomplished through biotechnological tools such as tissue culture and gene transfer (Ozyigit *et al.*, 2023). Tissue culture techniques, including callus culture, cell suspension culture, protoplast culture, and *in-vitro* micro-propagation, contribute to the enhanced production of secondary metabolites in medicinal plants (Siahsar *et al.*, 2011; Ozyigit *et al.*, 2023). The goal of micro-propagation is to rapidly obtain numerous clonal plants, facilitating the isolation of secondary metabolites from these clonal plants. In contrast, other tissue culture techniques aim to elevate the production rates of secondary compounds. The precise manipulation of secondary metabolite pathways in medicinal plants is achievable through the regulated control of endogenous or transferred genes using engineered zinc-finger proteins or transcription activator-like effectors. Gene transfer or recombinant DNA technology results in a higher yield of secondary compounds by modifying the secondary metabolite pathway (Sreenikethanam *et al.*, 2022). Genome editing methods such as TALENs, zinc-finger nucleases, and CRISPR-Cas facilitate the creation of customized medicinal plants. These targeted genome editing approaches significantly impact plant synthetic biology and offer novel avenues for the integration of medicinal plants into various industries. Selective breeding or regulated genetic modification can enhance desirable traits like increased medicinal compound content, disease resistance, or adaptation to specific growing conditions.

The bark of the *Taxus* tree is used for the production of an important diterpene alkaloid, Taxol (micro-tubule stabilizing property) that is widely used in synthesis of anti-cancer drugs and treatment of ovarian, breast and lung cancer (Weaver *et al.*, 2014). In order to overcome the low concentration of taxol in yew tree bark, seasonal variation in taxane concentration, and complex and expensive purification technology, plant cell culture is widely adopted for taxol production (Malik *et al.*, 2011). Another important plant with anti-tumor effect is periwinkle (*Cathranthus roseus*). The anti-cancerous effect of periwinkle is due to presence of dimeric alkaloids such as vinblastine and vincristine. *In-vitro* callus or cell suspension culture is widely used for achieving higher production rates of alkaloids. Genetic engineering and over-expression of biosynthetic rate limiting enzymes in alkaloid biosynthesis pathways is another approach followed in periwinkle (Alam *et al.*, 2017). Plumbagin, a quinoid compound obtained from roots of *Plumbago* sp. is identified as novel agent to treat hormone refractory prostate cancer in men (Hafeez *et al.*, 2013). Beigmohamadi *et al.* (2019) standardized the protocols of callus and cell suspension culture for large scale production of plumbagin from *Plumbago zeylanica.* Latex from the opium poppy, *Papaver somniferum*, is a commercial source of the analgesics, derived from alkaloids morphine and codeine. Various biotechnological techniques like callus culture; (Hodges and Henry, 1982); cell suspension culture (Siah and Pauline, 1991) and genetically modified plants with increased alkaloid production (Larkin *et al.* 2006) has been undertaken to promote the production volumes in opium poppy. Artemisinin (sesquiterpene lactone), isolated from *Artemisia annua* L., has anti-malarial bioactivity and is used to treat multi-drug resistant strains of falciparum malaria. Baldi and Dixit (2008) developed an integrated yield enhancement strategy for artemisinin cell suspension cultures.

Protoplast culture stands as an alternative tissue culture method aimed at achieving elevated rates of secondary metabolite production. Several instances highlight the extraction of secondary compounds through protoplast cultures, including the retrieval of indole alkaloids from *Catharanthus roseus* (Aoyagi *et al.*, 1998), the identification of chitinase, ajmalicine, and 5'-phosphodiesterase in *Wasabia japonica* and *Catharanthus roseus* (Akimoto *et al.*, 1999), and the isolation of scopolamine from *Hyoscyamus muticus* (Oksman-Caldentey and Strauss, 1986).

Nevertheless, certain compounds are not synthesized in undifferentiated cells, a limitation addressed by employing hairy root cultures generated through *Agrobacterium rhizogenes*-mediated transformation (Matveeva and Sophie, 2016). Hairy root cultures are frequently linked to a heightened biosynthetic capacity for the production of secondary metabolites in medicinal plants, surpassing that of non-transgenic roots. Hairy root culture is reported for production of several secondary compounds in medicinal plants like *Atropa belladonna* for scopolamine (Bonhomme *et al.*, 2000), *Artemisia annua* for artemisinin (Wang *et al.*, 2006), *Datura innoxia* for hysocyamine and scopolamine (Shimomura *et al.*, 1991), *Hyoscyamus niger* for hysocyamine and scopolamine (Shimomura *et al.*, 1991), *Papaver somniferum* for morphine, codeine (Le Flem-Bonhomme *et al.*, 2004), *Panax ginseng* for ginsenosides (Kunishi *et al.*, 1998), *Plumbago rosea* for plumbagin (Satheeshkumar *et al.*, 2009) *Rauvolfia micrantha* for ajmalicine and ajmaline (Sudha *et al.*, 2003), *Solanum khasianum* for solasodine (Jacob *et al.*, 2004), and *Withania somnifera* for withanolide A (Murthy *et al.*, 2008).

Conclusion

The cultivation of medicinal plants stands as a dynamic and intricate process, harmonizing traditional wisdom with contemporary scientific approaches. The amalgamation of diverse cultivation methods from meticulous soil preparation to precise harvesting techniques lays the groundwork for nurturing these plants and harnessing their potent therapeutic properties. Embracing sustainability, ethical practices, and regulatory compliance underpins the responsible cultivation of medicinal flora. As the demand for natural remedies and pharmaceutical alternatives grows, the cultivation of medicinal plants not only addresses health needs but also underscores the imperative of preserving biodiversity and respecting traditional wisdom. Thus, the cultivation of medicinal plants stands not only as a scientific endeavor but also as a testament to the delicate balance between human well-being, nature, and cultural heritage.

Conflict of interests

Authors declare no conflict of interests

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