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Shivam Kumar Lal
University Institute of Agriculture
Sciences, Chandigarh University,
Chandigarh, India

Shaina Walia
University Institute of Agriculture
Sciences, Chandigarh University,
Chandigarh, India

Shilpa Sukubhatu
University Institute of Agriculture
Sciences, Chandigarh University,
Chandigarh, India

Shilpa Kaushal
University Institute of Agriculture
Sciences, Chandigarh University,
Chandigarh, India

Corresponding Author:
Shivam Kumar Lal
University Institute of Agriculture
Sciences, Chandigarh University,
Chandigarh, India

Climate-resilient agronomic and nutrient management strategies for better yield and quality of medicinal and aromatic plants

Shivam Kumar Lal, Shaina Walia, Shilpa Sukubhatu and Shilpa Kaushal

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Abstract

Medicinal and aromatic plants (MAPs) are global commodities that are strategically important to pharmaceutical, cosmetic, food, and nutraceutical industries. The ever-growing risks of climate change such as the increase in temperatures, the change in the precipitation patterns, the increase in CO₂, drought, and the extreme weather conditions are proving to be a significant interference to the MAP cultivation systems, negatively affecting the harvestable yield as well as biosynthesis of therapeutically valuable secondary metabolites. In 2023, the global trade in MAP was USD 4.18 billion in exports with China and India as its top exporters, indicating the necessity of climate-adaptive production approaches. This review is a synthesis of literature in the field of 2020-2025 to: (i) evaluate the situation in the world in terms of production of MAPs, (ii) clarify the observed impact of climate change on its production and quality, and (iii) critically assess the agronomic and nutrient management strategies to address climate-resilience to maintain and enhance MAP productivity. Agronomic manipulations like optimum planting times, mulching, intercropping, deficit irrigation and protective cultivation are addressed with integrated nutrient management systems including balanced NPK, micronutrient application, arbuscular mycorrhizal fungi (AMF) inoculation, plant growth-promoting rhizobacteria, organic amendments and elicitor applications. The review provides an in-depth resource to researchers, agronomists, and policymakers aiming to achieve climate-adaptive, high-quality MAP cultivation systems.

Keywords: Climate change, medicinal plants, aromatic plants, secondary metabolites, nutrient management, agronomic practices, essential oil, drought stress, yield, quality

1. Introduction

Medicinal and aromatic plants (MAPs) are one of the oldest and most durable types of useful plants known to humankind. With a traditional and contemporary medicine, functional food, cosmetic and aromatherapy ingredient, and global flavor and fragrance industry foundation base of more than 17,000 species spread across over 50 botanical families, MAPs are used as the foundation raw material in conventional and contemporary medicine, functional food, cosmetic and aromatherapy formulations, and the entire flavor and fragrance industry (Zamani *et al.*, 2025) ^[22]. The ayurvedic herbs of the Indian subcontinent, the aromatic Lamiaceae of the Mediterranean basin, or the alkaloid-rich flora of tropical South America, MAPs are threads essential to the cultural, ecological and economic web of civilizations all around the world. The world MAP market is estimated to reach USD 410.3 billion in 2024 and is set to almost double to USD 890.7 billion by 2034 at a CAGR of 8.1, as more and more plant-based ingredients are integrated into mainstream healthcare, nutrition, and personal care.

The hallmark that separates MAPs and traditional food crops is their ability to synthesize and store a wide range of secondary metabolites such as alkaloids, terpenoids, flavonoids, phenolic acids, tannins, saponins, glucosinolates, and essential oils (EOs) that have therapeutic, aromatic, or pest-deterrent activities of commercial and pharmaceutical interest. They are not constitutive but are dynamically regulated by environmental cues, and their biosynthesis and accumulation are highly influenced by the abiotic conditions that the plant undergoes during its life cycle (Pant *et al.*, n.d.) ^[14]. Environmental cues such as light intensity, temperature, water availability, soil nutrient status, and UV radiation all regulate the expression of important biosynthetic genes and enzyme activities in terpenoid, phenylpropanoid, and alkaloid pathways.

This inherent environmental sensitivity implies that MAP quality in terms of secondary metabolite content and composition is much more susceptible to climate variability as compared to the quality of traditional starch or sugar crops.

It is on this background that climate change poses the greatest systemic risk that MAP production is facing in the world today. The Intergovernmental Panel on Climate Change (Intergovernmental Panel on Climate Change (IPCC), 2023) ^[8] estimates that average global temperatures will range between 1.5 and 4.0 °C in 2100, based on the greenhouse gas emission trends, with more frequent and severe drought and heat wave events, higher atmospheric levels of CO₂, and higher sea levels which pose a threat to coastal and delta agricultural lands. These are changes which are not future projections but realities. Iran is already producing significantly less saffron (*Crocus sativus*) than 50 years ago, and unusual heat and significantly lower winter rainfall in 2022-2023 have contributed to even lower production of 140 tons of saffron in 2023 compared to the long-term averages of 350-370 tons. *Nardostachys jatamansi*, *Swertia chirayita*, and *Aconitum* species are cold-adapted Himalayan medicinal species that are being documented to be undergoing an upwards altitudinal migration as a result of warming and are upsetting traditional harvesting regimes (Singh *et al.*, 2024) ^[18]. Combined climate-and-land-use change scenarios result in an effectively disproportionate risk of extinction of Mediterranean endemic MAP species (Kougioumoutzis *et al.*, 2024) ^[11].

Management of MAPs in agronomy under climate change needs a totally different paradigm as compared to the traditional management of cereal or vegetable crops. Since the commercially useful endproducts are not primary assimilates but secondary metabolites, management decisions have to be made to maximize two partially competing goals simultaneously; maximizing the harvestable biomass (yield) and maximizing the concentration and composition of the secondary metabolites (quality). Both goals are interfered with by climate change in a network of interacting processes heat and drought stress reduce biomass production, temperature-mediated changes in biosynthetic enzyme activity modulate metabolite profiles, high CO₂ results in biomass dilution and secondary metabolites concentrations, and disruption of soil microbiome reduces nutrient cycling and plant-microbe symbioses which maximize These issues require a combination of evidence-based agronomic and nutrient management practices aimed at climate resiliency that have been specifically tested in MAP production systems.

Though a single component of MAP agronomy has previously been reported to respond to water deficit (essential oil yield), or the impact of nitrogen-fertilization on the alkaloid content has been reviewed in isolation, an integrative, whole-system review has not yet been assembled that deals with the full spectrum of yield and quality goal in MAPs, under the conditions of water deficit. This is specifically important considering the escalating rate of climate change impacts that have been reported in the literature on climate change in 2020-2025 and the urgency in creating practical toolkits of adaptation to MAP producers, processors and policy stakeholders. The literature on arbuscular mycorrhizal fungi (AMF), growth-promoting rhizobacteria (PGPR), elicitor usage, silicon nutrition, and applied water management in MAPs has not been compiled in terms of the climate adaptation perspective, which poses a knowledge gap that this review fills.

The review is organized in a way that gives an in-depth logical flow of the topic. It starts with an evaluation of the international situation of MAP production and trade (Section 1), and then moves on to discussing the multidimensional significance of

MAPs along the pharmaceutical, economic, and ecological lines (Section 2). The main sections systematically discuss the reported impacts of climate change on MAP yield (Section 3) and quality (Section 4), and thoroughly discuss climate-resilient agronomic practices to improve yield (Section 5) and quality (Section 7), accompanied by similar reviews of nutrient management practices to improve yield (Section 6) and quality (Section 8). Section 9 sums up the main conclusions and outlines priority future research directions. Combined, these sections offer a comprehensive, evidence-based approach to the climate change issue in MAP production, relying solely on peer-reviewed literature published in the period between 2020 and 2025 to make sure that the information presented is up-to-date and relevant to the current research, practice, and policy implementation.

The scope limitations of this review should be noted. In line with the objectives and scope of the Journal of Applied Research on Medicinal and Aromatic Plants (JARMAP), the research presented in this review is based on the main production chain of MAP raw materials and their quality determinants, which include genetic resources, cultivation, physiology, nutrient management, and postharvest concerns that are directly related to secondary metabolite production and quality. Other areas of interest such as pharmacological activity, toxicology, ethnobotany, micropropagation and callus culture are clearly excluded. The review includes MAPs that are grown in conventional and organic management systems, in field and semi-controlled systems, in tropical, subtropical, temperate, Mediterranean, and arid/semiarid agro-climatic regions, which represents the global geographic and taxonomic variation in the MAP industry.

This review compilation has been performed with a careful consideration of the bibliographic standards of JARMAP, considering solely the 2020-25 publications available via Scopus, Google Scholar, or PubMed databases. In cases where market information and gray literature sources have been utilized to augment peer-reviewed results on global MAP market situations, they have been differentiated well with the citations of scientific literature. The review also favors multi-location experimental studies and metaanalytical reviews, as opposed to single-site observations, and uses a wide range of MAP genera (such as *Mentha*, *Ocimum*, *Salvia*, *Thymus*, *Origanum*, *Lavandula*, *Cymbopogon*, *Withania*, *Catharanthus*, *Panax*, *Matricaria*, *Foeniculum*, *Dracocephalum* and *Echinacea*, among others, to ensure broad representativeness of findings across the MAP sector.

1.1 Global Scenario of Medicinal and Aromatic Plants

The medicinal and aromatic plants (MAPs) are at the center of global agriculture, health, and trade. An indepth study of the international MAP trade using the International Trade Center data (HS code 1211) on the export and import values of 2010-2023 revealed that the global export and import values increased by 97.8% and 98.1% to USD 4.18 billion and USD 4.25 billion, respectively, in 2023 (Zamani *et al.*, 2025) ^[22] China and India became leading exporters with India registering a phenomenal 240 percent growth in export value over this time. In 2022, HS 121-190 which includes plants to perform perfumery, pharmacy and pest control dominated more than 90 percent of total MAP trade value worldwide. The quantity of MAPs sold each year is approximately 400,000 tons; yet, over 70% are extracted through wild collection, which causes significant doubts about the sustainability, preservation of biodiversity and quality stability (Zamani *et al.*, 2025) ^[22].

In 2024, the global MAP market is estimated to be USD 410.3 billion that is expected to expand to USD 890.7 billion by 2034 with a compound annual growth rate (CAGR) of 8.1%. Asia-Pacific region dominates the world MAP production having more than half of the market share. Ayurvedic products in India, where an excess of more than 8,000 species of medicinal plants are found, have grown 17% in exports in 2023, reaching USD 1 billion, and tulsi, ashwagandha, and giloy have seen a 40-50 percent rise in sales in 2022-2023. In the 2024 budget, the Government of India has allocated more than INR 4,300 crore to the AYUSH ministry a 20% rise compared to the past years in recognition of the national strategic value of MAPs. The global market size of the herbal medicinal products sector will grow by USD 271.1 billion in 2026 to USD 606.3 billion in 2036 at a compounded annual growth rate of 8.4 percent due to the rising popularity of natural remedies and the adoption of plant-based medicines into mainstream health care.

In spite of this remarkable market trend, the MAP industry has very serious structural susceptibilities. (Kougioumoutzis *et al.*, 2024) ^[11] evaluated how MAPs would respond to a combination of climate and land use alterations in a Mediterranean biodiversity hot spot, using a species distribution modelling approach on a set of endemic and non-endemic MAP species. Their results showed that endemic MAPs experience disproportionate habitat loss in predicted future conditions with mountainous areas being major transition areas in the range changes of the species. Moreover, shortages of raw materials (more than 30 percent of collected MAP species are at risk due to over-harvesting and land degradation) are also a structural supply burden complicating the effects of climate change. All these findings point to the fact that the global MAP sector is at a crossroads in which long-term market growth needs to be balanced with the ecological sustainability and climate resilience.

2. Importance of Medicinal and Aromatic Plants

2.1 Pharmaceutical and Therapeutic Significance

MAPs are the most important source of unparalleled variety of bioactive secondary metabolites alkaloids, terpenoids, flavonoid, phenolic acids, tannins, saponins and essential oils that form the basis of their therapeutic applications in both traditional and modern medicine systems. According to (Alum, 2024) ^[1], about one-fourth of contemporary pharmaceuticals are either directly or indirectly made of plant-based sources, and more than 80 percent of the world population in the developing world uses a primary healthcare based on plant-based medications. (Pant *et al.*, n.d.) ^[14] carried out a systematic literature review on how environmental conditions affect the content of secondary metabolites and verified that abiotic conditions such as temperature, light intensity, water and mineral nutrition have a strong regulatory impact on the biosynthetic pathways leading to the production of these compounds. *Catharanthus roseus* (vincristine, vinblastine), *Artemisia annua* (artemisinin), *Withania somnifera* (withanolides) and *Ocimum sanctum* (eugenol, rosmarinic acid) are among the pharmaceutically most important MAPs. (Yeshi *et al.*, 2022) ^[21] summarized the pharmacological potential of stress-responsive plant secondary metabolites and highlighted their usefulness in drug discovery, highlighting the reliance of the pharmaceutical industry on high-quality and consistent production of MAPs.

2.2 Economic Importance and Industrial Applications

In addition to pharmaceuticals, MAPs provide an intricate network of industries. (Zamani *et al.*, 2025) ^[22] have observed that the world MAP market is growing by 10-20 per cent per

annum with the value of the market under the pure trade of more than USD 68 billion including processed derivatives. Lamiaceae aromatics (lavender, peppermint, thyme, oregano, rosemary, sage, basil) and Poaceae grasses (lemongrass, palmarosa, citronella) are essential oils that have a high price in the fragrance, food flavoring, and cosmetic sectors. In a review article published in *Frontiers in Plant Sciences*, (Mansinhos *et al.*, 2024) ^[13] emphasized that the popularity of MAPs has soared over the last few years due to the rising demand in natural products in the cosmetics, pharmaceuticals, and functional foods sectors. It showed that inter planting MAPs with companion crop always led to better essential oil (EO) production and composition, optimal plant growth, and better economic returns especially when used with organic inputs or biofertilizers proving that smart agronomic design benefits not only production efficiency but also marketable output quality.

2.3 Ecological and Conservation Value

MAPs play vital ecological functions in addition to their direct economic and medicinal uses. Most MAP species are keystone resources to pollinators and beneficial insects, and provide ecosystem services such as pollination and biological pest control. (Kougioumoutzis *et al.*, 2024) ^[11] highlighted that mountainous Mediterranean ecosystems are the main repositories of localized MAP diversity that should be given priority conservation because these ecosystems are under simultaneous stress due to climate change and increased land-use intensity. (Groner *et al.*, n.d.) ^[7] also determined that climate change along with landcover change and overharvesting threaten widely used medicinal plant species, with species in climate-vulnerable geographic areas with severe near-term extinction risks. Sustainable utilization of MAPs is becoming a key component of One Health models that connect ecosystem health, conservation of biodiversity and human wellbeing.

3. Effect of Climate Change on Yield and Quality of Medicinal and Aromatic Plants

Climate change acts on MAP production systems through two interconnected and equally important pathways: (i) direct suppression of harvestable yield through biomass reduction, phenological disruption, and habitat loss; and (ii) alteration of secondary metabolite biosynthesis pathways that define MAP quality. Both pathways are reviewed in an integrated manner below, as they share common climate drivers and frequently interact in determining overall MAP production value.

3.1 Temperature Stress: Effects on Yield and Secondary Metabolite Quality

One of the most deterministic abiotic factors that regulate the MAP productivity and quality is temperature. The (Intergovernmental Panel on Climate Change (IPCC), 2023) ^[8] estimates a global warming of between 1.5-4.0o C by 2100 in varying emission scenarios, which has significant implications on the global agricultural systems. (Alum, 2024) ^[1] confirmed that the rapid increase in CO₂ and temperatures are placing compounding stress on the development, yield, and quality of MAPs and that heat stress causes cascade morphological, physiological, and biochemical changes. The heat stress at the critical phenological processes-germination, anthesis and seed set-damages the cell membrane integrity, enzyme activity and reduces the viability of the reproductive organs resulting in low harvestable yield of different MAP species. According to (Mansinhos *et al.*, 2024) ^[13], frequency and intensity of heat waves are expected to rise considerably, exacerbating the occurrence of droughts and cumulative abiotic stress loads of aromatic plants.

At the same time, temperature has a significant impact on the quality of secondary metabolites. As reported by (Mansinhos *et al.*, 2024) ^[13], temperature regulates the expression of important biosynthetic genes in the methylerythritol phosphate (MEP) and mevalonate pathways involved in the biosynthesis of mono- and sesquiterpene. Heat stress (exceeding 35°C) in Lamiaceae aromatics suppresses geranyl diphosphate synthase activity, leading to a direct decrease in EO production and a change in chemical composition to less desirable chemotypes. (Alum, 2024) ^[1] observed that heat stress in *Catharanthus roseus* decreases accumulation of the anticancer vinca alkaloids vinblastine and vincristine by impaired tertiary metabolism, whereas in peppermint, high temperatures prefer menthofuran over menthol accumulation—severely lowering commercial oil quality. Transcriptomic data by (Jo *et al.*, 2022) ^[10] of CO₂ and temperature interaction effects on fennel expression of flavonoid biosynthesis pathway genes showed the molecular complexity of the interaction between climate quality and CO₂ and temperature. The experience of the world speaks volumes: the output of saffron decreased more than 60 percent in 50 years, and a temperature rise of 2.8°C and a 52 percent decrease in winter rainfall in 2022–2023 led to the production of only 140 tons of saffron per year versus 350–370 tons in the long term.

3.2 Drought and Water Deficit: Yield Losses and Dual Quality Effects

The effects of climate change on MAP crops are water-deficit stress due to altered precipitation patterns and higher drought frequency, which have direct effects on biomass accumulation, yield, and quality of secondary metabolites. Experimentally, (Gasemi *et al.*, 2023) ^[6] showed under field conditions that extreme water stress led to significantly lower dry weight biomass yield of *Dracocephalum kotschyi*, whereas it showed that a combination of drought and heat stress resulted in additive or synergistic yield losses that are greater than either stressor alone—a scenario that is becoming increasingly prevalent. Drought stress and secondary metabolite quality have a non-linear relationship. Moderate drought, through reactive oxygen species (ROS)-mediated induction of phenylalanine ammonia-lyase (PAL) and chalcone synthase (CHS) synthesis, was confirmed in the Frontiers in Pharmacology scoping review (2025) as a way to increase biosynthesis of protective phenolics and flavonoids. (Gasemi *et al.*, 2023) ^[6] proved that AMF + PGPR inoculation of water along with mild water stress in *D. kotschyi* yielded the greatest geranyl acetate (11.4–18.88%), geranial (9.23–11.91%), and limonene (5.56–9.12) content in EO, which highlights. On the other hand, extreme and long-term drought finally diminishes the quality of EO by oxidatively damaging the enzymes of terpenoid biosynthesis and enhancing leaf senescence (Pant *et al.*, n.d.) ^[14]. MAPs that grow in semi-arid and Mediterranean areas are increasingly subjected to climate conditions that are increasingly drying, posing a danger to the established production systems unless adaptive management is implemented.

3.3 Elevated CO₂: Yield Stimulus and Quality Dilution

The CO₂ levels in the atmosphere, which are now over 420 ppm, have a CO₂ fertilization effect on C3 MAP species. (Jo *et al.*, 2022) ^[10] experimentally demonstrated that elevated CO₂ induced significant alterations in plant growth, transcriptome, and antioxidant activity in fennel (*Foeniculum vulgare* Mill.), with documented biomass increases accompanying modifications in metabolic pathways regulating bioactive compound biosynthesis. In C3 plants, higher levels of CO₂ usually improve photosynthetic carbon fixation and water-use efficiency. However, the resulting biomass dilution effect often lowers the concentrations of secondary metabolites on a dry weight basis, which is a quality issue even when total yield goes up (Alum, 2024) ^[1].

3.4 UV-B Radiation and Photochemical Quality

Climate change has caused higher levels of UV-B radiation, which triggers the production of phenolic and flavonoid compounds in MAPs. (Mansinhos *et al.*, 2024) ^[13] recorded that UV-B induces the expression of UV-absorbing flavonoids and hydroxycinnamic acid derivatives in epidermal tissues as photoprotective mechanisms, enhancing rosmarinic acid levels in *Salvia* and *Melissa* species and augmenting anthocyanin accumulation in *Ocimum basilicum*. But too much UV-B exposure can damage DNA and stop PSII electron transport, which is bad for plant growth and the production of bioactive compounds when photoinhibition thresholds are crossed.

3.5 Soil Microbiome Disruption, Distribution Shifts, and Biodiversity Threats

Climate change changes the temperature, moisture levels, and rates of organic matter decomposition in the soil. These changes have a ripple effect on the soil microbial communities that are important for the quality of MAP secondary metabolites. (Zhao *et al.*, 2022) ^[22] demonstrated that AMF colonization reconfigures plant metabolic pathways, augmenting secondary metabolite production via nutritional and signaling mechanisms. The climate-induced disruption of these beneficial soil-plant symbioses has substantial indirect effects on MAP quality that necessitate management-level interventions.

Climate change is changing the way suitable MAP habitats are spread out across regions and the world, not just on individual farms. (Kougiomoutzis *et al.*, 2024) ^[11] discovered that endemic MAPs experience significantly greater habitat loss compared to non-endemic species in Mediterranean hotspots. (Groner *et al.*, n.d.) ^[7] demonstrated that climate change, land-cover alteration, and overharvesting jointly jeopardize commonly utilized South African medicinal plant species, forming a multi-driver vulnerability framework relevant worldwide. These distributional disruptions have significant consequences for conventional harvesting methods, indigenous knowledge systems, and the pharmaceutical industry's ability to maintain a reliable supply of raw materials.

Table 1: Effects of climate change stressors on yield and secondary metabolite quality of medicinal and aromatic plants (MAPs)

Climate Stressor	Effect on Yield	Effect on Quality	MAP Species/Evidence	Citation
Rising temperature (>35 °C heat stress)	Impairs germination, anthesis & seed set; reduces biomass; shortens crop duration	Downregulates geranyl diphosphate synthase (MEP/MVA pathway); shifts EO chemotypes; reduces vinca alkaloids in <i>C. roseus</i>	<i>Catharanthus roseus</i> ; <i>Mentha piperita</i> ; <i>Lamiaceae</i> aromatics; <i>Crocus sativus</i> (60% yield decline in Iran)	A(Alum, 2024; Mansinhos <i>et al.</i> , 2024) ^[1, 13]
Drought/ Water deficit	Severe stress significantly reduces dry biomass; combined drought + heat causes synergistic losses	Moderate stress upregulates phenolics & flavonoids (ROS-PAL-CHS pathway); severe stress degrades EO quality	<i>Dracocephalum kotschyi</i> ; <i>Lavandula latifolia</i> ; <i>Lallemantia royleana</i>	(Gasemi <i>et al.</i> , 2023; Pant <i>et al.</i> , n.d.) ^[6, 14]
Elevated CO ₂ (>420 ppm)	CO ₂ fertilisation increases biomass in C3 MAPs; enhances WUE	Biomass dilution reduces secondary metabolite concentration per dry weight unit; alters transcriptome and antioxidant metabolome	<i>Foeniculum vulgare</i> (fennel); C3 <i>Lamiaceae</i> aromatics	(Alum, 2024; Jo <i>et al.</i> , 2022) ^[1, 10]
Elevated UV-B radiation	Excessive UV-B inhibits PSII electron transport; reduces plant growth	Moderate UV-B acts as elicitor of phenolics & flavonoids; increases rosmarinic acid (<i>Salvia</i> , <i>Melissa</i>) & anthocyanins (<i>Ocimum</i>)	<i>Salvia</i> spp.; <i>Melissa officinalis</i> ; <i>Ocimum basilicum</i>	(Mansinhos <i>et al.</i> , 2024) ^[13]
Soil microbiome disruption	Disruption of AMF symbiosis reduces nutrient acquisition and root biomass support	Loss of AMF-mediated phytohormonal signalling reduces trichome density and secondary metabolite biosynthesis	Broad MAP systems; <i>Rosmarinus officinalis</i> ; <i>Lavandula angustifolia</i>	(Pasquini <i>et al.</i> , 2023; Zhao <i>et al.</i> , 2022) ^[15, 23]
Habitat/range shifts	Altitudinal migration narrows cultivation zones; endemic species face disproportionate habitat loss	Wild-harvested material becomes less available; quality consistency from wild populations compromised	<i>Nardostachys jatamansi</i> ; <i>Swertia chirayita</i> ; Mediterranean endemics	(Groner <i>et al.</i> , n.d.; Singh <i>et al.</i> , 2024) ^[18]

Abbreviations: EO = essential oil; WUE = water-use efficiency; MEP = methylerythritol phosphate; MVA = mevalonate pathway; ROS = reactive oxygen species; PAL = phenylalanine ammonia-lyase; CHS = chalcone synthase; AMF = arbuscular mycorrhizal fungi; FC = field capacity.

4. Agronomic Practices for Enhancing Yield and Quality of Medicinal and Aromatic Plants

Climate-resilient agronomic strategies must simultaneously optimize harvestable yield and secondary metabolite quality-two objectives that are partially competing but can be reconciled through integrated management. The following practices address both dimensions comprehensively.

4.1 Planting Time, Density, and Crop Geometry Optimization

One of the easiest and cheapest ways for farmers to deal with climate change is to change their sowing and planting schedules to fit phenological windows that have been adjusted for climate change. Moving transplanting times to avoid the hottest or driest times of year during important growth stages has been shown to work for many MAP species. Early sowing strategies take advantage of leftover soil moisture and cooler temperatures at the start of the season to avoid heat stress that could kill plants during the reproductive stages. Optimizing the density of plant populations also controls the microclimate in the canopy, lowers competition for water and nutrients between plants, and increases light interception, which is important as climate change makes high-temperature radiation events more common.

4.2 Mulching for Soil Moisture Conservation and Temperature Regulation

Mulching is a very useful and well-proven agronomic instrument to maintain soil moisture, moderate soil temperature extremes, suppress weeds and enhance soil health-properties of particular relevance as climate stress increases. A synthesis of research revealed that plastic film mulches are more effective in preventing soil evaporation, in comparison to organic mulches, especially at the initial stages of crop growth. (Biswas & Das,

2024) ^[2] affirmed that mulching blends well in the organic farming systems to curb both the abiotic and biotic stresses. Mulching has a two-fold adaptation advantage in climate change: it lowers irrigation needs and it maintains a moderate root zone temperature that influences plant growth and secondary metabolite synthesis.

4.3 Intercropping and Agroforestry Systems

Companion crops Intercropping MAPs with compatible companion crops has several climate adaptation advantages: microclimate moderation, enhanced soil health, decreased pest pressure, and diversified income. Saffron intercropped with chickpea in various irrigation regimes retained high yields of saffron, enhanced soil fertility and a land equivalent ratio (LER) of 1.86-reflecting great intercropping productivity benefit. Cymbopogon species interplanting with legumes and food crops continued to enhance EO yield and composition, boosted soil microbial activities, and offered effective weed management benefits. The agroforestry combination of medicinal tree with ground-level herbal MAPs offers heat and UV radiation stress moderation of the shade, lesser evapotranspiration, and understorey microclimates that are conducive to shade-adapted medicinal species (Maitra *et al.*, 2021) ^[12].

4.4 Water Management: Deficit Irrigation and Micro-Irrigation

Effective management of water is the key to maintaining MAP productivity and quality in the everincreasing droughty conditions. Smart drip irrigation systems can achieve a similar level of irrigation reduction and healthy plant growth, and water savings are recorded in a variety of MAP species (Franco-Navarro *et al.*, 2025) ^[5]. Deficit irrigation has been demonstrated to sustain MAP yields in acceptable ranges at 50-

80 percent of crop evapotranspiration (ET_c) and conserve 30-45 percent of water used during full irrigation. Notably, deficit irrigation can also play a role as a quality improvement agent: moderate levels of water stress (50-70% ET_c) can always be used to induce secondary metabolite generation by activating stress-signaling pathways (Gasemi *et al.*, 2023) ^[6]. AMF inoculation with 75% field capacity irrigation in sage (*Salvia officinalis*) resulted in the highest herb dry biomass yield, and high EO content (1.361%), compared to fully irrigated and severely stressed treatments. Drip irrigation combined with mulching and inoculation with biofertilizer now forms the most fully-validated water-conserving production system of high-value MAP crops under waterrestricted conditions.

4.5 Shade Nets, Protective Structures, and Microclimate Management

Shade nets (25-50 percent shading), windbreaks and low tunnels that protect against heat stress, UV radiation damage, and adverse weather effects have significant benefits in sensitive MAP crops. The physiological benefits of managing light in shade-intolerant plants such as more efficient photosynthate allocation to carbon-intensive secondary metabolite synthesis and lower carbon loss of photosynthesis. The deployment of shade net is especially successful with *Stevia rebaudiana*, *Bacopa monnieri* and forest understory medicinal herbs where shade levels 25-30 percent increase steviol glycoside and bacoside concentrations respectively. On the other hand, the Mediterranean aromatic herbs (thyme, oregano, lavender, rosemary) that are acclimated to open, high-irradiance conditions yield greater EO content when grown under full sunlight. Shade management strategies that are matched to the species-specific photobiological needs is thus a crucial element in quality-centered MAP agronomic management.

4.6 Harvest Time Optimization for Quality

The most important agronomic determinant of the quality of MAP is the timing of harvest in reference to the phenological stage of the plant. By increasing or slowing the phenological development unpredictably, climate change makes timing of harvests more difficult. The peak level of menthol occurs at the end of the pre-bloom to the early bloom stage in peppermint, late harvest causes rapid menthol degradation and menthofuran build-up. In chamomile (*Matricaria chamomilla*), α -bisabolol and chamazulene peaks occur concurrently with the open-petal flower stage of flower development. Portable spectrophotometry or near-infrared spectroscopy real-time monitoring, where the secondary accumulation stages are identified by the actual accumulation of the secondary metabolite, without using the calendar date, is becoming more and more popular and allows more adaptive, quality-oriented harvest management.

4.7 Elicitor Applications for Quality Enhancement

Elicitors-biotic or abiotic stimuli leading to plant defence reaction and secondary metabolite biosynthesis-are an ever-growing tested agronomic instrument to enhance MAP quality. (Selwal *et al.*, 2023) ^[17] affirmed that jasmonic acid (JA), methyl jasmonate (MeJA), salicylic acid (SA), chitosan, and silicon are viable elicitors on a variety of MAP species at the right concentrations and developmental stages. Directly showing that AMF-mediated methyl jasmonate signaling increased saponin accumulation in *Panax notoginseng*, (Dai *et al.*, 2024) ^[3] provided an indication of synergistic interactions between elicitors and mycorrhizas in enhancing the quality of alkaloids-a result that has widespread implications on alkaloid-producing MAPs such as *Catharanthus roseus* and *Withania somnifera*.

4.8 Post-Harvest Management and Quality Preservation

Post-harvest drying method and temperature directly determine the final quality of MAP commodities by affecting the stability of thermolabile secondary metabolites, essential oil composition, flavonoid content, and alkaloid integrity. (Vogel *et al.*, 2014) ^[19] established that vacuum and freeze drying preserve secondary metabolites significantly more effectively than convective drying methods in lemon balm (*Melissa officinalis* L.). Under climate change scenarios, elevated ambient temperatures during harvest seasons increase the urgency of rapid, low-temperature processing adoption to preserve the quality gains achieved through climate-resilient agronomic management.

4.9 Climate-Adapted Germplasm Selection and Variety Development

The development and deployment of climate-resilient MAP varieties with improved heat tolerance, drought resistance, and stable high yield and quality potential under stress conditions represents a highimpact long-term agronomic strategy. (Singh *et al.*, 2024) ^[18] reviewed sustainable techniques for harvest and conservation of medicinal plant species and emphasized the critical role of genetic resource conservation and strategic germplasm deployment. (Selwal *et al.*, 2023) ^[17] identified genetic improvement through molecular breeding and transgenic approaches as among the most promising strategies for enhancing secondary metabolite production stability under climate stress in MAPs.

5. Nutrient Management Strategies to Increase Yield and Quality of Medicinal and Aromatic Plants

Nutrient management is both a yield-determining and quality-determining factor in MAP production. Optimal nutrition simultaneously supports biomass accumulation and secondary metabolite biosynthesis, while imbalanced nutrition can improve yield at the expense of quality or vice versa. An integrated nutrient management (INM) approach addressing both objectives is therefore essential for climateadaptive MAP production.

5.1 Macronutrient Management: Nitrogen, Phosphorus, and Potassium

In MAP crops, the accumulation of vegetative biomass and harvestable yield are controlled by nitrogen (N). (Fang *et al.*, 2023) ^[4] showed that optimum NPK fertilization enhanced growth and yield greatly by enhancing the stability of soil microbial community structure and nutrient cycling activity by using multiyear field experiments on *Chrysanthemum morifolium*. It determined the best NPK concentrations of *Origanum dubium* in hydroponic culture and discovered that moderate N (150 mg L⁻¹), P (75 mg L⁻¹), and K (350mg L⁻¹) in nutrient solution were optimal in growth properties and water-use performance. Of primary importance, the correlation between nitrogen nutrition and the quality of secondary metabolites is often inverse-excessive N is more likely to decrease EO and phenolic compound levels and stimulate vegetative growth. In *O. dubium*, Plants that were grown in low N concentration (75 mg L⁻¹) had higher total phenols, antioxidant capacity, and p-cymene content in EO even though the fresh weight was lower than that of higher N concentrations. The reverse of this is that N management of MAP production will have to balance the growth and secondary metabolism goals by splitting application strategies and precisely calibrating the rates. In climatic conditions of climate change, where soil N cycling is more and more perturbed by the extremes in

temperature and moisture availability, the slow release N sources and nitrification inhibitors provide better N synchrony with crop demand, minimizing N loss and risks of quality dilution.

Phosphorus (P) supports root development, energy transfer, and biosynthetic pathway activation, while K improves drought tolerance, enzyme activation, and photosynthate translocation-functions of particular importance under climate stress. N300 levels in *Sideritis cyprica* produced the highest mineral accumulation, nutrient, and water-use efficiency. Potassium fertilization has been shown to boost yield and quality of medicinally important crops by promoting malic acid metabolism and enhancing accumulation of health-promoting phytochemicals (Franco-Navarro *et al.*, 2025) ^[5]. Adequate K levels may further enhance production of phenolic compounds and other secondary metabolites that aid in plant defense (Franco-Navarro *et al.*, 2025) ^[5].

5.2 Secondary Macronutrients: Sulfur, Calcium, and Magnesium

Sulfur (S) is an element of structural components of major secondary metabolites such as glucosinolates, alliin, volatile sulfur compounds that establish the therapeutic and aromatic properties of a variety of medicinally and aromatic plants. *Allium sativum* S sufficiency In *Allium sativum*, alliin is synthesized and converted enzymatically to allicin-the main antimicrobial agent when tissue is disrupted. In citronella (*Cymbopogon nardus*), (Gasemi *et al.*, 2023) ^[6] indicated that synergistic increase of both biomass yield and EO content were achieved with the combined use of AMF biofertilizers and Mg SO₄ at 285 kg ha⁻¹, which validates the interactive advantages of combined Mg and AMF management on aromatic MAP productivity.

5.3 Micronutrient Management and Secondary Metabolite Biosynthesis

Micronutrients serve as catalytic components of key enzymes in secondary metabolite biosynthesis pathways. Zinc (Zn) is a cofactor for geranyl diphosphate synthase, directly influencing monoterpene biosynthesis, while iron (Fe) is essential for cytochrome P450 enzymes involved in hydroxylation steps of alkaloid and phenolic biosynthesis. Climate change-induced soil pH shifts and altered redox conditions increasingly risk micronutrient deficiencies in MAP cultivation systems, making proactive micronutrient monitoring and supplementation a climate adaptation necessity.

5.4 Biofertilizers: AMF, PGPR, and Their Synergistic Benefits

Biofertilizers are environmentally sustainable, climate-resilient alternatives or supplements to chemical fertilisers for management of MAP nutrients. (Zhao *et al.*, 2022) ^[23] reviewed AMF and MAP interactions, providing evidence that colonization of AMF increases production of secondary metabolites via both nutritional (increased plant uptake of water and P) and signalling (reprogramming of biosynthetic pathways via phytohormonal changes and ROGs) mechanisms. Therefore, the symbiotic relationships formed between AMF and plants increases the development of glandular trichomes on aromatic plants the sites of EO production-improving both EO yield per plant and overall biomass gains in plants.

(Gasemi *et al.*, 2023) ^[6] provided evidence demonstrating that combined application of AMF and PGPR together with *D. kotschyi* plants showed elevated Yield and Quality irrespective of water stress. Higher Yield and Quality of EO included higher

numbers of Geranyl Acetate, Alpha-Pinene, and Geranial, compared to either PGPR or AMF alone. (Pasquini *et al.*, 2023) ^[15] found that AMF inoculated plants of *Rosmarinus officinalis* and *Lavandula angustifolia*, exhibited far superior growth and biochemical parameters vs. non-mycorrhizal plants with significant enhancement under conditions of limited moisture availability. According to (Wahab *et al.*, 2023) ^[20], countries that have incorporated AMF technologies have demonstrated superior economic returns in the productivity and quality enhancement of MAPs compared to countries using only conventional methods of growing MAPs in response to the combined effects of different abiotic stress caused by climate change.

Quality-wise, (Zhao *et al.*, 2022) ^[23] showed that AMF colonization leads to increased density of glandular trichomes and significantly increases rosmarinic Acid, Terpenoids, phenolics, and alkaloid accumulation in many different types of MAP. Additionally, (Dai *et al.*, 2024) ^[3] demonstrated that there is a molecular connection through which AMF enhances the quality of alkaloids by enhancing the effects of methyl jasmonate (produced by AMF) on the alkaloid concentration of *P. notoginseng*. Lastly, (Rasouli *et al.*, 2023) ^[16] confirmed that the relationship between AMF and MAP changes both primary and secondary metabolites profiles; the accumulations of terpenoids, phenolics, and alkaloids have been consistently shown to be greater than when AMF were not present versus when they were present.

5.5 Organic Amendments and Integrated Nutrient Management (INM)

The most climate-resilient comprehensive nutrient management system to use in MAP cultivation is Integrated Nutrient Management (INM)-combining prudent chemical fertilization with organic manures, biofertilizers, and green manures. INM enhances soil organic carbon, water-holding capacity, microbial diversity, and cation exchange capacity: all of which serve to buffer MAP performance to temperature extremes, drought events, and waterlogging events that are becoming more and more linked to climate change. (Javanmard *et al.*, 2022) ^[9] showed in peppermint (*Mentha piperita*) that, when used in both monoculture and intercropping system with biofertilizers and organic manure, combinations of green manure significantly increased the productivity, EO percentage and composition, and menthol content in comparison with chemical fertilization alone. Such quality gains in case of organic amendment management are quite applicable in case of climatic change where the depletion of organic matter in soils due to high temperature lowers the ability of soils to buffer nutrient supply.

5.6 Silicon as an Emerging Nutrient for Quality and Stress Resilience

Silicon (Si) is not a classical essential plant nutrient, but a very useful mineral element in promoting MAP quality in the stressful climatic conditions. Si deposition in cell walls enhances mechanical barriers, decreases cuticular water loss, enhances heat and drought tolerance, and modulates the quality of secondary metabolites by acting on stress signaling pathways and antioxidant enzyme activities. Si can moderate temperature and water stress responses, which implies that Si can be used to maintain the quality gains of secondary metabolites anticipated in mild stress situations and avoid the quality losses experienced in harsh stress situations that are becoming more frequent with climate change (Yeshi *et al.*, 2022) ^[21]. Since there is little published research on Si in MAP systems, in particular, it is an area of priority in future research.

Table 2: Summary of climate-resilient agronomic and nutrient management strategies for enhancing yield and quality of medicinal and aromatic plants

Strategy	Category	Yield Benefit	Quality Benefit	Citation
Regulated deficit irrigation (50-80% ETc) + drip	Agronomic	Maintains yield within acceptable ranges; reduces water use by 30-45%	Mild water stress activates ROS-mediated secondary metabolite biosynthesis; highest EO content at 75% FC in sage	(Franco-Navarro <i>et al.</i> , 2025; Gasemi <i>et al.</i> , 2023) ^[5, 6]
Mulching (plastic or organic)	Agronomic	Conserves soil moisture; moderates root-zone temperature; reduces irrigation frequency	Stabilises root-zone temperature, preserving secondary metabolite biosynthesis enzyme activity	(Biswas & Das, 2024) ^[2]
Intercropping with companion crops	Agronomic	LER up to 1.86 (saffron-chickpea); improved soil fertility and weed management	Improved EO yield and composition in <i>Cymbopogon</i> spp.; glycine betaine application mitigates heat stress on corn quality	(Maitra <i>et al.</i> , 2021) ^[12]
Elicitor applications (MeJA, SA, chitosan)	Agronomic	Promotes biomass allocation via stress priming; synergy with AMF enhances plant productivity	Upregulates phenylpropanoid, terpenoid & alkaloid biosynthesis; saponin accumulation in <i>Panax notoginseng</i> increased by AMF-mediated MeJA signalling	(Dai <i>et al.</i> , 2024; Selwal <i>et al.</i> , 2023) ^[3, 17]
Shade net management (25-50% shading)	Agronomic	Reduces heat and UV-B damage in sensitive MAPs; improves photosynthate partitioning	Enhances steviol glycosides (<i>Stevia rebaudiana</i>) and bacosides (<i>Bacopa monnieri</i>) under 25-30% shade	(Yeshe <i>et al.</i> , 2022) ^[21]
Optimised NPK fertilisation	Nutrient Management	Optimal N-P-K supply maximises biomass and yield; reinforces soil microbial community and nutrient cycling	Low-to-moderate N enhances EO phenolics and antioxidant capacity; balanced K boosts phenylpropanoid pathway enzymes	(Fang <i>et al.</i> , 2023; Wahab <i>et al.</i> , 2023) ^[4, 20]
AMF + PGPR biofertiliser inoculation	Nutrient Management	Improves P & water uptake, root biomass, and drought tolerance; synergistic AMF + PGPR produces highest EO yield under mild water stress	Increases glandular trichome density; enhances EO content, rosmarinic acid, terpenoids, phenolics and alkaloids through nutritional + signalling mechanisms	(Gasemi <i>et al.</i> , 2023; Pasquini <i>et al.</i> , 2023; Wahab <i>et al.</i> , 2023; Zhao <i>et al.</i> , 2022) ^[6, 15, 20, 23]
Integrated Nutrient Management (INM) with organic amendments	Nutrient Management	Improves soil organic carbon, WHC, microbial diversity, and CEC; buffers nutrient supply against climate variability	Organic management increases EO percentage, menthol content, and phenolic compounds compared to chemical fertilisation alone	(Javanmard <i>et al.</i> , 2022) ^[9]
Silicon (Si) application	Nutrient Management	Strengthens cell walls; reduces cuticular water loss; improves heat & drought tolerance supporting biomass	Preserves stress-responsive secondary metabolite biosynthesis pathways under heat and drought; modulates antioxidant enzyme activity	(Yeshe <i>et al.</i> , 2022) ^[21]

Abbreviations: ETc = crop evapotranspiration; FC = field capacity; LER = land equivalent ratio; EO = essential oil; NPK = nitrogen-phosphorus-potassium; AMF = arbuscular mycorrhizal fungi; PGPR = plant growth-promoting rhizobacteria; INM = integrated nutrient management; WHC = water-holding capacity; CEC = cation exchange capacity; MeJA = methyl jasmonate; SA = salicylic acid; Si = silicon.

6. Conclusion

This peer-reviewed literature review (2020-25) offers strong evidence that climate change is causing multidimensional and more damaging negative impacts on MAP production systems around the world. Increased temperatures, severe instances of drought, a rise in the amount of atmospheric CO₂, an increase in UV-B radiation, and alteration of the microbiome community in the soil pose a threat to both the quantity and quality of MAPs in terms of the harvestable crop and to the quality of the secondary metabolites that characterize the commercial and pharmaceutical usefulness of MAPs. Practical experience supports the existence of these as realities on the ground: the production of saffron in Iran has fallen by more than 60% in half a century; endemic MAP species in Mediterranean biodiversity hotspots are losing habitat disproportionately (Kougioumoutzis *et al.*, 2024) ^[11]; and widely used medicinal species are The economic need to implement effective and science-based climate adaptation in MAP cultivation is clear with the global MAP exports amounting to USD 4.18 billion in 2023 and the global market estimated to reach USD 890.7 billion by 2034 ((Zamani *et al.*, 2025) ^[22]).

Climate change impacts on MAPs operate through two distinct but interconnected pathways: (i) yield-level suppression through biomass reduction, phenological disruption, and habitat loss; and (ii) molecular-level disruption of secondary metabolite

biosynthesis pathways—modifying the composition and concentration of essential oils, alkaloids, flavonoids, and phenolic acids in ways that can reduce pharmaceutical efficacy and commercial value even when biomass yields remain acceptable (Alum, 2024; Mansinhos *et al.*, 2024) ^[1, 13]. The dual nature of these impacts demands management responses that simultaneously address both objectives.

There is a strong and proven set of agronomic responses to the climate that can be deployed. Mulching is effective at regulating high and low temperatures of the soil and preserving moisture (Biswas & Das, 2024) ^[2]. Drip delivery systems with regulated deficit irrigation (50-80% ETc) maintain MAP productivity and use 30-45% less water, as well as improves the quality of secondary metabolites by mild stress signaling. Quality MAPs intercropped with compatible companion species enhance microclimate moderation, soil health, and system land equivalent ratio of over 1.0. Specific biomolecules Elicitor applications—in particular, methyl jasmonate, salicylic acid, chitosan—provide targeted means of inducing upregulation of particular biosynthetic pathways (Dai *et al.*, 2024; Yeshe *et al.*, 2022) ^[3, 21]. AMF inoculation—the most repeated and validated biological intervention in the recent literature on MAP—enhances drought tolerance, nutrient uptake, glandular trichome density, and secondary metabolite biosynthesis by both nutritional and signaling pathways ((Pasquini *et al.*, 2023; Wahab *et al.*, 2023;

Zhao *et al.*, 2022)^[15, 20, 23]. 20 AMF + PGPR biofertilizer interaction yields synergistic advantages to both yield and EO quality in conditions of water-deficit (Gasemi *et al.*, 2023)^[6]. Together, integrated nutrient management and agronomic practices are key to climate-responsive MAP production systems that can provide predictable yield and quality performance over an ever more variable growing environment.

7. Future Perspective

Despite the substantial advances reviewed herein, significant knowledge gaps remain that must be addressed through targeted, multi-disciplinary research programs. The following priority research directions emerge from critical analysis of the current literature.

First and foremost, there is an urgent need to create MAP-specific process-based crop models that combine climate projections and agronomic management decisions. In contrast to large-scale cereals and vegetables, MAPs do not have the validated crop growth simulation models that could forecast the yield and secondary metabolite responses across a variety of climate conditions. These models need to include explicitly secondary metabolite biosynthesis sub-routines—a significant technical problem that demands the combination of agronomic, physiological and molecular biological expertise. Second, field trial manipulations on multi-location, multi-year scales that test agronomically-optimized, biofertilizer, nutrient and elicitor-management integrated climate-adaptive management packages are urgently required in contrasting agro-climatic regions. Most of the existing research analyses individual management factors separately and at single sites, which limit the statistical quality and generalizability of results.

Third, transcriptomic, proteomic, and metabolomic investigations that clarify the molecular pathways through which climate stressors reprogram secondary metabolites biosynthesis pathways in MAPs are needed to be able to design quality management strategies rationally. The use of multi-omics on priority MAP species experiencing heat, drought, UV-B, and CO₂ would provide the mechanistic insight to design precision management interventions to address particular biosynthetic bottlenecks. Fourth, transformational long-term investment is the accelerated development and deployment of stress-tolerant types of MAP by using technologies of marker-assisted selection, genomic selection, and precision gene editing (including CRISPR/Cas9). Critical conditions are that stress tolerance gains need to occur without affecting the secondary metabolite content, composition, or stability-demanding routine secondary metabolite profiling as part of the selection and evaluation pipelines.

Fifth, optimization of combined strategies of biostimulant-elicitor-nutrient management in yield and concomitant quality improvement during and under climate stress is a very promising and fast developing area. High-value information on optimal combinations, application timing, and interaction mechanisms of various MAP species and climate stress types would be produced through systematic factorial experiments that would be used to manage precision MAP production. Sixth, there is a need to conduct more research on the socioeconomic and policy aspects of climate-adaptive MAP production. Smallholder farmers who have little access to capital, inputs and extension services do most of the global MAP production especially in Asia and Africa. Agronomy, agricultural economics, rural sociology, and policy science interdisciplinary studies are required to realize the agronomic and nutrient management improvements discussed herein into practical and scalable and

equitable adaptation outcomes to farming communities worldwide that rely on MAPs. The ultimate cross-disciplinary effort to tackle climate resilience in MAP cultivation needs to be coordinated investment and collaboration across the entire research-to-practice spectrum.

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