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Review

Weed Management in Medicinal and Aromatic Plants: Current Strategies and Future Perspectives—A Narrative Review

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Abstract

Weeds represent a major constraint in the cultivation of medicinal and aromatic plants (MAPs), causing significant reductions in yield, biomass, and essential oil quality while increasing labor and production costs. Effective weed management is particularly critical during early crop growth, when young plants are most vulnerable to competition. Non-chemical strategies, including cultural practices, mechanical and thermal weeding, mulching, and crop diversification, have proven effective in suppressing weeds, enhancing crop competitiveness, and maintaining yield and quality, especially in organic or low-input systems. Mulching and optimized cultivation strategies consistently provide reliable weed control, improve soil moisture and nutrient use efficiency, and can influence secondary metabolite accumulation. Chemical weed control, including selective pre- and post-emergence herbicides, remains important in slow-growing MAPs but is increasingly constrained by regulatory restrictions and concerns over residues in raw plant material and essential oils. Integrated weed management combining cultural, physical, and reduced chemical approaches offers the most effective solution, balancing efficacy, crop safety, and product quality. Emerging strategies such as bioherbicides, precision agriculture, and robotic systems hold promise but require further research. Advancing weed management in MAPs will depend on interdisciplinary studies, field-scale validation, and technology-driven innovations to support sustainable, high-quality production.

Keywords: mulching; cultural practices; crop diversification

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1. Introduction

Weeds are usually defined as plants growing where they are not wanted, especially in agricultural systems, where they compete with crops for nutrients, light, water, and space, thereby reducing yield and quality [1,2]. In the cultivation of medicinal and aromatic plants (MAPs), weeds pose a major challenge, leading to significant reductions in yield, biomass, and product quality while also increasing production costs [3,4]. Yield losses due to weeds in MAPs can be severe, ranging from 35% to 90% depending on the species and management practices [5–8]. The composition and dynamics of weed flora in MAP systems are strongly influenced by the weed seed bank, which acts as a reservoir of viable propagules in the soil. They are also shaped by climatic and environmental factors such as temperature, precipitation, and light, which affect germination and establishment. In addition, many weed species also occur as associated or volunteer plants in crop stands due to overlapping ecological niches and reproductive strategies [9,10]. Weeds can significantly reduce essential oil yield and alter its composition, with reported reductions of up to 60–80% in species such as *Angelica archangelica* L. and *Mentha arvensis* L. [11,12], in addition to direct competition and allelopathic effects [13]. Furthermore, weed infestation increases labor requirements, production costs, and risks of biomass contamination, potentially compromising product quality and safety due to the presence of toxic compounds such as pyrrolizidine and tropane alkaloids [5,14–21].

MAPs are increasingly important globally, contributing to the pharmaceutical, cosmetic, and food industries, and the economic and ecological value of these crops underscores the need for effective cultivation practices [22,23]. Given the high value of MAP products and concerns about pesticide residues, non-chemical and integrated weed management strategies are particularly relevant, as they help safeguard product quality while maintaining yield [24,25].

The critical period for weed control in MAPs generally occurs during early crop growth, when young plants are most vulnerable to competition. In *Satureja hortensis* L., weed interference begins shortly after sowing and extends to mid-season, significantly reducing essential oil yield and altering composition [26]. In *Mentha arvensis*, the most sensitive periods were 30–75 days after planting for the first harvest and 15–45 days for the second, with early weed pressure strongly decreasing herb and oil yield, plant height, and leaf-to-stem ratio [12,27]. Similarly, in *Mentha piperita* L., weed presence reduced biomass and essential oil yield, while hand weeding and higher planting density improved crop growth and yield [28]. Slow initial growth and poor canopy development, as observed in crops like *Curcuma longa* L., further increase vulnerability to weed competition during early growth stages [7]. The vulnerability of young plants during this critical early growth phase underscores the need for timely, species-specific, and integrated weed management strategies.

Despite the recognized impact of weeds on yield, essential oil quality, and crop economics, comprehensive reviews addressing both chemical and non-chemical management strategies in MAPs remain limited, highlighting a knowledge gap and the importance of integrative assessments. This narrative review aims to provide a comprehensive and structured synthesis of weed management strategies in MAP cultivation, encompassing preventive, physical, cultural, and chemical approaches, as well as emerging technologies, with a particular emphasis on sustainable and integrated practices.

2. Experimental Approaches to Weed Control in MAPs

This review draws on information from several major databases, including ScienceDirect, Springer Nature, Web of Science, Scopus, and Google Scholar. The search was conducted using the keywords "weed management" and "medicinal and aromatic plants" in titles, abstracts, and keywords. Studies were included if they investigated weed management, reported experimental, field, or modeling results, and included a control; review articles were excluded.

A diverse set of non-chemical strategies, including cultivation practices, physical methods, mulching, and crop diversification, has been reported to effectively suppress weeds, enhance crop competitiveness, and maintain yield and quality in MAPs. Additionally, chemical weed management is often used as a control in experiments, so it is also included. These approaches form a foundation for sustainable and integrated weed management, as summarized in Table 1.

Table 1. Experimental approaches to non-chemical physical and biological weed control in MAPs: methods and controls.

Plant Species	Common Name	Preventive Cultural Practices	Mechanical Treatment /Positive Control *	Mulching				Thermal Treatment	Crop Diversification (Intercropping or Living Mulches)	Herbicide (Common Name)	Weedy Plot (Negative Control) **	Reference
				Synthetic	Natural	Inorganic	Without (or Conventional, or Not Specified)					
Achillea millefolium	Yarrow	–	hand weeding	black polypropylene, black polyethylene	–	–	–	–	–	–	–	[29]
Anethum graveolens	Dill	–	–	polythene mulch	straw mulch	–	+	–	–	–	–	[30]
Anethum graveolens	Dill	–	regular mechanical weeding	white polypropylene textile and transparent perforated foil	–	2 cm sand layer and 5 cm peat moss mixed with top layer of the soil	–	–	–	–	–	[31]
Angelica archangelica	Garden angelica	–	hand weeding	agro-textile foil and silver-brown foil	sawdust of acacia and oak mixture and wheat straw	–	–	–	–	Metamitron and Aclonifen	+	[32]
Angelica archangelica	Garden angelica	–	hand weeding	agro-textile foil and silver-brown foil	sawdust of acacia and oak mixture and wheat straw	–	–	–	–	–	+	[11]
Artemisia annua	Sweet wormwood	–	–	–	rice straw mulch	–	+	–	–	–	–	[33]
Calendula officinalis	Pot marigold	–	–	black mulch, yellow mulch and transparent mulch	–	–	+	–	–	–	–	[34]
Coriandrum sativum	Coriander	false seedbed	hand weeding	biodegradable plastic mulch	–	–		flaming	–	–	–	[35]
Coriandrum sativum	Coriander	–	hand weeding	black polyethylene mulch	rice straw	–	–	–	–	Glyphosate, Pendimethalin, Butraline, Metribuzin, Prometryn, and Linuron	+	[36]
Coriandrum sativum	Coriander	–	hand weeding	–	–	–	+	–	–	Pendimethalin, Fluchloralin, Oxadiazon, and Propanil	+	[37]
Coriandrum sativum	Coriander	–	–	–	–	–	+	–	*Capsicum annuum*			[38]
Coriandrum sativum	Coriander	–	–	–	–	–	+	–	*Trigonella foenum-graecum*	–	–	[39]
Coriandrum sativum	Coriander	–	–	–	–	bagana mulch (4–16 t/ha)	+	–	–	–	–	[40]
Crocus sativus	Saffron	–	–	plastic mulch	grass cutting	–		–	–	–	+	[41]
Crocus sativus	Saffron	–	–	–	sawdust mulch	–	+	–	–	–	–	[42]

Table 1. *Cont.*

Plant Species	Common Name	Preventive Cultural Practices	Mechanical Treatment /Positive Control *	Mulching				Thermal Treatment	Crop Diversification (Intercropping or Living Mulches)	Herbicide (Common Name)	Weedy Plot (Negative Control) **	Reference
				Synthetic	Natural	Inorganic	Without (or Conventional, or Not Specified)					
Cuminum cyminum	Cumin	–	–	–	wheat straw	–	+	–	–	Trifluralin and Pendimethalin	–	[43]
Cymbopogon martini	Palmarosa	pre-sowing irrigation	hand weeding	–	–	–	–	–	–	–	–	[44]
Cymbopogon sp.	Lemongrass	–	hand weeding	–	post-distillation solid residues of *C. winterianus*	–	–	–	–	Oxyfluorfen, Diuron, and Simazine	+	[45]
Cymbopogon winterianus	Java citronella	–	hand weeding	–	post-distillation solid residues of *C. winterianus*	–	+	–	*Vigna mungo*	Diuron	+	[46]
Dracocephalum moldavica	Moldavian dragonhead	–	hand weeding	–	wheat straw	–	+	–	–	Trifluralin and Pendimethalin	+	[47]
Echinacea purpurea	Purple coneflower	–	–	polyethylene brown and black plastic mulches, poly-fiber black and white plastic	paper mulch (gray-colored, recycled, degradable material for field mulching)	–	+	–	–	–	–	[48]
Foeniculum vulgare	Fennel	false seedbed	hand weeding	biodegradable plastic mulch	–	–	–	flaming	–	–	–	[35]
Foeniculum vulgare	Fennel	–	hand weeding	–	wheat straw	–	–	–	–	Trifluralin and Pendimethalin	+	[49]
Foeniculum vulgare	Fennel	–	hand weeding and interculture	silver-black plastic mulch	–	–	–	–	–	Pendimethalin and Fenoxaprop-ethyl	–	[50]
Helichrysum italicum	Immortelle	–	–	black polypropylene film	straw mulch and alfalfa hay mulch	–	+	–	–	–	–	[51]
Hyssopus officinalis	Hyssop	–	–	polyethylene brown and black plastic mulches, poly-fiber black and white plastic	paper mulch (gray-colored, recycled, degradable material for field mulching)	–	+	–	–	–	–	[48]
Lallemantia iberica	Dragon's head	–	–	–	–	–	+	–	*Cicer arietinum*	–	–	[52]
Lavandula angustifolia	Lavender	–	hand weeding	black transpiring mulch and black draining mulch	–	–	–	–	–	–	–	[53]

Table 1. *Cont.*

Plant Species	Common Name	Preventive Cultural Practices	Mechanical Treatment /Positive Control *	Mulching				Thermal Treatment	Crop Diversification (Intercropping or Living Mulches)	Herbicide (Common Name)	Weedy Plot (Negative Control) **	Reference
				Synthetic	Natural	Inorganic	Without (or Conventional, or Not Specified)					
Lavandula angustifolia	Lavender	–		polyethylene, transpiring, draining types	–	–	+	–	–	–	–	[54]
Lavandula angustifolia	Lavender	–	–	black plastic mulch	–	–	+	–	–	–	–	[55]
Lavandula angustifolia	Lavender	–	–	mulch foil	straw	–	+	–	–	–	–	[56]
Matricaria chamomilla	Chamomile	–	–	–	rice straw, black gram straw and barnyard millet straw	–	+	–	–	–	–	[57]
Melissa officinalis	Lemon balm	–	–	–	scattering the mustard seed meal on the surface of plots	–	–	–	–	Bentazon and Fluazifop-p−butyl	+	[15]
Melissa officinalis	Lemon balm	–	finger weeder, torsion weeder, rotary weeder, tine harrow, ridging technique, hand-drawn hoes, hand weeding	–	–	–	+	–	–	–	–	[58]
Melissa officinalis	Lemon balm	–	–	black polypropylene film	–	–	+	–	–	–	–	[59]
Melissa officinalis	Lemon balm	–	–	polyethylene brown and black plastic mulches, poly-fiber black and white plastic	paper mulch (gray-colored, recycled, degradable material for field mulching)	–	+	–	–	–	–	[48]
Mentha × piperita	Peppermint	–	hand weeding	–	–	–	–	–	–	–	+	[28]
Mentha × piperita	Peppermint	–	hand weeding	silver-brown and black “agrotextile” film	sawdust of acacia and dry pine needles	–	–	–	–	–	+	[60,61]

Table 1. *Cont.*

Plant Species	Common Name	Preventive Cultural Practices	Mechanical Treatment /Positive Control *	Mulching				Thermal Treatment	Crop Diversification (Intercropping or Living Mulches)	Herbicide (Common Name)	Weedy Plot (Negative Control) **	Reference
				Synthetic	Natural	Inorganic	Without (or Conventional, or Not Specified)					
Mentha arvensis	Menthol mint		hand weeding	–	–	–	–	–	–	Propaquizafop-p−ethyl, Clodinafop propargyl, Pendimethalin, Oxyfluorfen, Imazethapyr and Imazamox	+	[62]
Mentha arvensis	Menthol mint	–	hand weeding	–	–	–	–	–	–	Propaquizafop and Fenoxaprop-p−ethyl	+	[12]
Mentha arvensis	Menthol mint	–	–	–	rice straw mulch	–	+	–	–	Diuron	+	[63]
Mentha arvensis	Menthol mint		hand weeding	–	wheat straw	–	–	–	–	Terbacil, Pendimethalin, Oxyfluorfen, Oxadiazon, Fluazifopbutyl, Diuron	+	[27]
Mentha spicata	Spearmint	–	–	–	straw mulch	–	+	–	–	–	–	[64]
Nigella sativa	Black cumin	–	–	silver-black polythene, black polythene,	organic mulch (not specified)	–	+	–	–	–	–	[65]
Ocimum basilicum	Sweet basil		hand weeding	polythene	straw	–	+	–	–	Pendimethalin	+	[6]
Ocimum basilicum	Sweet basil	–	hand weeding	black plastic	wood chips	–	–	–	–	–	–	[66]
Ocimum basilicum	Sweet basil	–	hand weeding	black plastic mulch	–	–	–	–	–	Napropamide, Glyphosate	–	[67]
Ocimum basilicum	Sweet basil	–	–	black plastic and black fabric	compost and straw	–	+	–	–	–	–	[68]
Origanum syriacum	Syrian oregano	–	–	–	pine needles	–	+	–	–	–	–	[69]
Origanum vulgare ssp. *hirtum*	Greek oregano		hand weeding (hand-pushed rotary tiller)	–	–	–		flaming	–	Cycloxydim, Glyphosate, Metribuzin, Pendimethalin	+	[70]
Pelargonium graveolens	Rose geranium	–	–	black, white, and silver-colored plastic mulch	–	–	+	–	–	–	–	[71]
Pelargonium spp.	Rose geranium	–	hand weeding	–	post-distillation solid residue of *Cymbopogon* sp.	–	+	–	–	Oxyfluorfen and Pendimethalin	+	[72]

Table 1. *Cont.*

Plant Species	Common Name	Preventive Cultural Practices	Mechanical Treatment /Positive Control *	Mulching				Thermal Treatment	Crop Diversification (Intercropping or Living Mulches)	Herbicide (Common Name)	Weedy Plot (Negative Control) **	Reference
				Synthetic	Natural	Inorganic	Without (or Conventional, or Not Specified)					
Petroselinum crispum	Parsley	–	hand weeding	black plastic mulch	–	–	–	–	–	Napropamide, Glyphosate	–	[67]
Petroselinum crispum	Parsley	–	finger weeder, torsion weeder, rotary weeder, tine harrow, ridging technique, hand-drawn hoes, hand weeding	–	–	–	+	–	–	–	–	[58]
Plantago psyllium	Blond psyllium	false seedbed	hand weeding	biodegradable plastic mulch	–	–		flaming	–	–	–	[35]
Pogostemon cablin	Patchouli	–	–	silver-black plastic mulch	rice straw mulch	–	+	–	–	–	–	[73,74]
Rosmarinus officinalis	Rosemary	–	hand weeding	black transpiring mulch and black draining mulch	–	–	–	–	–	–	–	[53]
Rosmarinus officinalis	Rosemary	–	–	polyethylene, transpiring, draining types	–	–	+	–	–	–	–	[54]
Rosmarinus officinalis	Rosemary	–	hand weeding	black plastic mulch	–	–	–	–	–	Napropamide, Glyphosate	–	[67]
Salvia sclarea	Clary sage		–	–	pine needles	–	+	–	–	–	–	[75]
Satureja hortensis	Summer savory	–	hand weeding	–	–	–	–	–	–	–	+	[26]
Satureja hortensis	Summer savory	–	–	–	–	–	+	–	*Zea mays*	–	–	[76]
Satureja montana	Winter sawory	–	–	polypropylene woven fabric	–	–	+	–	–	–	–	[77]
Satureja sahendica	–		hand weeding								+	[78]
Thymus vulgaris	Thyme	–	hand weeding	black transpiring mulch and black draining mulch	–	–	–	–	–	–	–	[53]
Thymus vulgaris	Thyme	–	–	polyethylene brown and black plastic mulches, poly-fiber black and white plastic	paper mulch (gray-colored, recycled, degradable material for field mulching)	–	+	–	–	–	–	[48]

* Positive control refers to standard weed management practices (e.g., regular mechanical weeding or hand weeding); ** Negative control (weedy plot) indicates untreated plots where weeds were allowed to grow without intervention; + indicates that the treatment was applied; – indicates that the treatment was not applied.

3. Preventive Cultivation Practices Influencing Weed Control

Preventive cultivation practices applied prior to crop establishment, such as pre-sowing irrigation and the false seedbed technique, can effectively reduce weed emergence in MAPs by stimulating germination of non-dormant weed seeds and lowering subsequent weed density and labor requirements [79,80]. In *Cymbopogon martini* (Roxb.) Will.Watson, repeated pre-sowing irrigations combined with minimal hand weeding significantly reduced weed density and biomass while maintaining seedling growth [44]. Although mechanical weeding, flaming, and mulching reduced weed biomass by 50–95%, the false seedbed often delayed crop establishment and negatively affected early growth, resulting in 40–90% lower seed yields compared with untreated plots, limiting its suitability despite good weed control in *Coriandrum sativum* L., *Foeniculum vulgare* Mill., and *Plantago psyllium* L. crops [35]. In contrast, cultivation practices during crop growth enhance weed suppression indirectly by improving crop competitiveness; in *Satureja sahendica* Bornm., optimized nutrient management and planting patterns improved crop–weed interactions and increased thymol content without significantly affecting weed density [78], highlighting the value of integrated, non-chemical weed management approaches. A brief summary of preventive cultivation practices with examples of good agricultural practices (GAP) in MAP cultivation is presented in Figure 1.

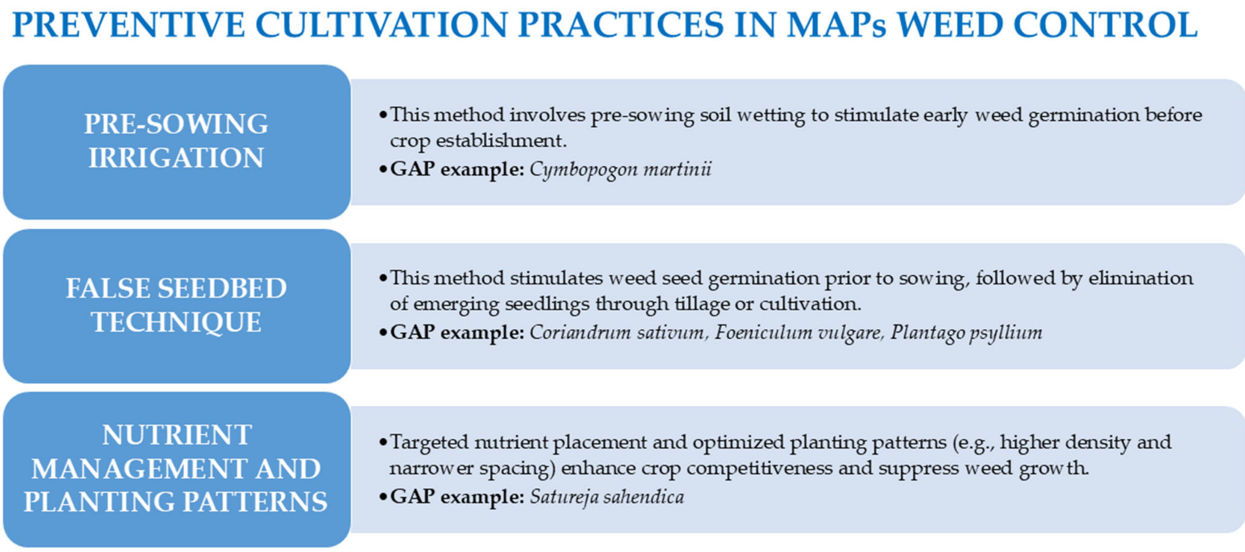

Figure 1. Overview of preventive cultivation practices and examples of good agricultural practices (GAP) applied in medicinal and aromatic plant (MAP) cultivation.

4. Physical Methods as Non-Chemical Weed Management Strategy

Non-chemical physical weed control methods include mechanical weeding, thermal techniques such as flaming, and mulching, which provide sustainable options for managing weeds in MAP cultivation (Figure 2). In experimental studies, herbicide treatments are often included as a reference to assess the efficacy of these non-chemical approaches, while untreated, weed-infested plots serve as a negative control.

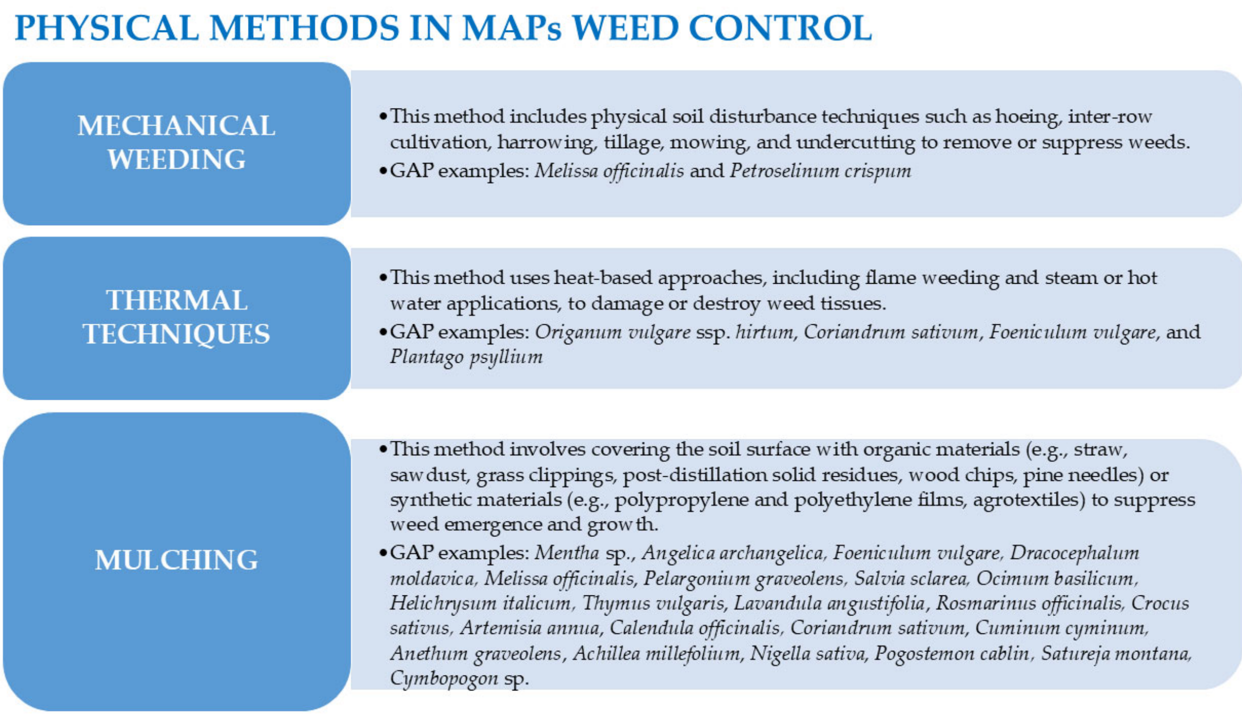

Figure 2. Overview of physical methods and examples of good agricultural practices (GAP) applied in medicinal and aromatic plant (MAP) cultivation.

4.1. Mechanical Weeding

Mechanical methods include hand and mechanical weeding, such as hoeing, inter-row cultivation, harrowing, tillage, mowing, and undercutting [81]. Regular mechanical weeding and hand weeding using a hand hoe or hand-pushed rotary tiller are commonly used as control methods in experiments [6,11,12,26,28,31,32,35–37,44–47,49,50,53,60–62,66,67,70,72,78,82]. To date, only one study has examined other mechanical methods in detail [58]. This study evaluated the performance of five mechanical intra-row weeding devices (finger, tine harrow, ridger share, torsion, and rotary weeders) in MAPs, specifically *Melissa officinalis* L. and *Petroselinum crispum* (Mill.) Fuss, during the critical establishment phase. Across eight field trials, weed control efficacy varied widely, with tine harrows and finger weeders showing greater applicability at early growth stages, while rotary weeders caused the most crop damage. Yield reductions were generally limited and inconsistent, and no single device consistently outperformed the others. These results indicate that, despite technological advances, mechanical intra-row weeding alone cannot yet fully replace herbicides, highlighting the need for a combination of complementary non-chemical and integrated weed management approaches and further research under variable field conditions.

4.2. Thermal Weeding

Thermal weed management uses heat to suppress or kill weeds without chemical herbicides by rapidly raising plant tissue temperatures, thereby disrupting cellular structures [83]. The efficacy of thermal weed control is highly variable and depends on several agronomic and environmental factors, including weed growth stage, with younger plants being significantly more susceptible than mature individuals, as well as species-specific tolerance linked to morphological and physiological traits [84,85]. Environmental conditions such as humidity, wind, and soil moisture can further influence heat transfer efficiency and treatment outcomes [86]. In addition, the intensity and duration of heat exposure play a critical role in determining cellular damage and overall weed mortality, which explains the inconsistent results reported across studies [87]. Common thermal techniques include flame weeding and steam or hot water applications. Flame weeding, often applied with propane burners, is the most widely studied method and is particularly effective on young broadleaf weeds, as it causes intracellular water to vaporize and ruptures cell membranes. This method is widely used in both organic and conventional agriculture [88]. Steam and hot water treatments provide a lower fire-risk alternative to open flames, transferring heat to weed plants and seeds to induce dehydration and death [89]. Overall, thermal methods show promise as part of integrated weed management but are limited by high energy requirements, variable efficacy among weed species, and the need for further technological refinement for precise and cost-effective field use, particularly under conditions where application parameters can be carefully optimized [90]. From an economic perspective, the adoption of these methods depends strongly on labor availability, energy costs, and farm scale, which may limit their practical applicability despite their environmental benefits.

Field experiments conducted over three growing seasons evaluated non-chemical (flaming) weed management strategies in comparison with chemical (pre- and post-emergence herbicide) treatments in *Origanum vulgare* L. ssp. *hirtum* (Link) Ietswaart [70]. Although none of the treatments provided complete weed control, flaming achieved moderate suppression but caused severe phytotoxicity and the greatest reductions in *Origanum vulgare* growth and essential oil yield. Post-emergence herbicide applications were the most effective, providing the highest weed control while maintaining *Origanum vulgare* performance comparable to the weed-free control. These results highlight the potential role of flaming as a non-chemical weed management practice. However, its negative impact on crop tolerance limits its standalone use, emphasizing the need for careful integration with chemical control methods. Further studies on herbicide residues in oregano are required before practical implementation.

Considering that MAPs are increasingly produced under organic systems, where effective non-chemical weed control is critical due to the negative effects of weeds on yield and quality [35], a four-year field experiment on *Coriandrum sativum*, *Foeniculum vulgare*, and *Plantago psyllium* tested several alternatives, including mechanical weeding, flaming, false seedbeds, and biodegradable mulch. Flaming proved to be one of the most effective strategies, reducing weed biomass by up to 95 percent without delaying sowing or negatively affecting crop performance. Overall, flaming provided efficient weed suppression while maintaining crop productivity, making it a promising method for organic cultivation of MAPs.

4.3. Mulching

A recently published review addressed mulching as a sustainable, non-chemical weed management strategy in the cultivation of MAPs, evaluating the effectiveness of organic, synthetic, and living mulches in suppressing weeds and improving crop yield [91]. The review discussed the mechanisms of mulch action, including light interception, physical suppression, and microclimate modification, as well as their effects on soil properties and secondary metabolite biosynthesis. Overall, the findings indicate that mulching effectively reduces weed biomass, enhances crop performance, and supports organic farming systems, although its effectiveness depends on mulch type, application rate, crop species, and agroecological conditions. Numerous studies further confirm mulching as a highly effective non-chemical weed management strategy in MAP cultivation, as summarized in Table 1.

Mulching, both organic and synthetic, is a highly effective non-chemical strategy for weed suppression, yield improvement, and quality enhancement in MAPs. In *Mentha piperita*, synthetic mulches such as silver-brown film and black agrotextiles nearly completely suppressed weeds and maximized biomass and essential oil yields [60,61]. Similar benefits were observed in *Angelica archangelica*, where black and silver-brown agrotextiles achieved complete weed control, improved fresh root yields, and influenced essential oil composition [11,32]. In *Foeniculum vulgare* and *Dracocephalum moldavica* L., integrating straw or plastic mulches with reduced herbicide application enhanced weed suppression, increased biomass, and improved essential oil yield [47,49,50]. In *Melissa officinalis*, black polypropylene mulch combined with higher planting density provided full weed control and maximized long-term economic returns [59]. Similarly, *Pelargonium graveolens* L'Hér. showed enhanced biomass with plastic mulches regardless of fertilizer application [71].

Straw mulching in *Mentha spicata* L. under rainfed Mediterranean conditions improved essential oil yield, mitigated photosynthetic inhibition, and influenced monoterpene composition, including carvone formation [64]. In *Salvia sclarea* L., mulching combined with partial substitution of chemical nitrogen with organic manure optimized soil temperature and moisture, enhancing plant growth, essential oil yield, and soil health [75]. Organic mulches, such as wood chips, consistently improved growth, yield, essential oil content, and water use efficiency in *Ocimum basilicum* L. under different irrigation regimes [66,68]. Black polyethylene mulch increased fresh and dry weight in basil and rosemary, whereas parsley showed no response, highlighting species-specific effects [67]. In *Helichrysum italicum* (Roth) G. Don, alfalfa and straw mulches differentially influenced flower yield, essential oil content, and bioactive compounds [51]. Black polypropylene mulches also supported growth and weed suppression in *Thymus vulgaris* L., *Lavandula angustifolia* Mill., and *Rosmarinus officinalis* L., proving suitable for marginal agricultural areas [53].

Mulching benefits extend to high-value crops such as *Crocus sativus* L. and *Artemisia annua* L., where polyethylene and sawdust mulches reduced weed pressure, conserved soil moisture, and improved vegetative and reproductive performance, corm development, and secondary metabolite accumulation [33,41,42]. In *Calendula officinalis* L. and *Coriandrum sativum*, black polythene or rice straw mulches combined with nutrient management or mechanical weeding significantly increased growth, flowering, seed yield, and essential oil content while suppressing weeds [34,36]. In *Cuminum cyminum* L., wheat mulch combined with reduced herbicide doses reduced weed biomass and improved growth, yield, and essential oil [43].

Other studies highlight mulching effects on soil microclimate and plant physiology. In *Anethum graveolens* L., polythene mulches enhanced plant height, branching, and seed yield under drip irrigation [30,31]. Mulches also positively influenced secondary metabolite production, as shown for *Achillea millefolium* L., *Lavandula angustifolia*, and *Nigella sativa* L., where organic or reflective polythene mulches improved essential oil and bioactive compound accumulation under optimal irrigation [29,55,65].

In long-term trials, polypropylene woven fabric mulch in *Satureja montana* L. and straw mulch in *Pogostemon cablin* Benth. improved water use efficiency, weed suppression, and drought resilience, although excessive moisture retention in clay soils occasionally increased pathogen pressure [73,74,77].

In addition to commonly used synthetic and natural mulches, post-distillation solid residues can also serve as valuable raw materials for mulching [92]. For example, post-distillation solid residues of *Cymbopogon* sp., when applied as mulch in the same crop, were found to be more effective than other weed management practices, including manual weeding or herbicide application, during the first year of cultivation, a period characterized by slow crop growth and high susceptibility to weed competition [45,46]. On the other hand, mulching with post-distillation solid residues of *Cymbopogon* sp., applied in *Pelargonium* sp. during the critical period of weed interference, specifically 45 days after planting and covering the first 90 days after planting, proved to be an effective cultural weed management practice [72].

Collectively, these studies demonstrate that both synthetic and organic mulches are integral to sustainable, non-chemical weed management in MAPs. Mulching improves weed control, optimizes water and nutrient use, enhances growth and yield, and can influence essential oil composition and bioactive compounds, making it a key practice for environmentally friendly and economically viable MAP cultivation.

5. Crop Diversification as Non-Chemical Weed Management Strategy

Crop diversification through the integration of medicinal plants into diversified cropping systems enhances agroecosystem sustainability by improving soil health, stimulating microbial activity, and increasing both land-use efficiency and overall crop productivity compared to simplified monocultures [93,94]. Studies show that intercropping or rotating MAPs with food crops can optimize resource use, contribute to effective pest and weed management, and support biodiversity while potentially improving yields and economic returns in sustainable agriculture [95,96]. Figure 3 summarizes key crop diversification practices and provides examples of good agricultural practices applied in MAP production.

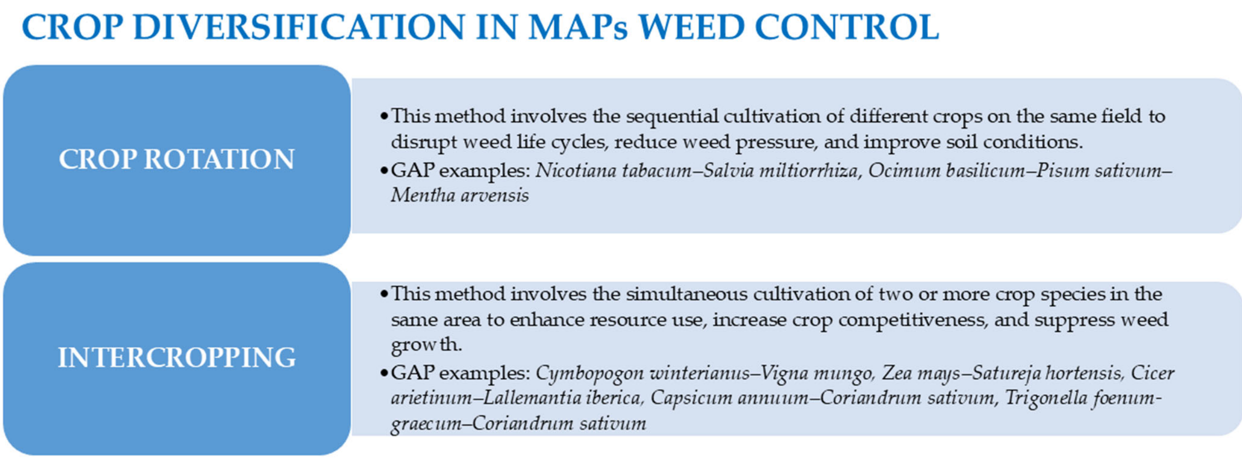

Figure 3. Overview of crop diversification methods and examples of good agricultural practices (GAP) applied in medicinal and aromatic plant (MAP) cultivation.

Continuous monocropping significantly reduces the growth, yield, and quality of *Salvia miltiorrhiza* Bunge, resulting in economic losses [97]. Crop rotation with tobacco has therefore been suggested as a strategy to optimize cultivation cycles by reshaping the soil microbial community structure [98]. Additionally, a study evaluating different cropping systems found that the sequence *Ocimum basilicum* (rainy season crop), *Pisum sativum* L. (winter season crop), and *Mentha arvensis* (summer season crop) generated the highest economic returns, including the greatest gross and net income, daily profit, and benefit–cost ratios [99]. These findings highlight that, beyond their ecological benefits, diversification strategies can also improve the economic efficiency of weed management by reducing reliance on external inputs and stabilizing yields. This diversified annual cropping system proved particularly effective in increasing farmers' income while maintaining high yields, demonstrating the economic potential of incorporating aromatic plants into conventional crop rotations.

A recently published review paper addressed the intercropping of MAPs with other crops, such as cereals, legumes, vegetables, and perennial species, as a strategy for sustainable agriculture [96]. Across numerous MAP species, intercropping was shown to improve land-use efficiency, crop productivity, and essential oil yield and quality, often resulting in higher economic returns, particularly when combined with organic inputs or biofertilizers [100,101]. Beyond productivity, these systems provided important ecological benefits by enhancing soil fertility, stimulating microbial activity, increasing biodiversity, and contributing to effective pest and weed management [102,103]. The integration of MAPs into orchards, vineyards, and agroforestry systems further demonstrated their multifunctional role in influencing secondary metabolite production and overall agroecosystem performance [104–106]. Overall, intercropping is presented as an economically viable and environmentally sustainable approach, with its success depending on appropriate species selection, planting ratios, and sound agronomic management [96]. A growing body of evidence confirms intercropping as an effective non-chemical weed management approach in MAP production. However, only a limited number of studies explicitly consider weed management as the direct research objective [38,39,46,52,76], as presented in Table 1.

Intercropping has emerged as an important ecological component of non-chemical weed management in MAP production systems, where herbicide options are limited and crop competitiveness is often weak during establishment. By increasing canopy cover, improving spatial resource use, and enhancing crop competition, intercropping systems can suppress weed growth while simultaneously stabilizing yields. In perennial *Cymbopogon winterianus* Jowitt, weed pressure markedly reduced herb and essential oil yields, underscoring the importance of early weed control; however, although intercropping with *Vigna mungo* contributed to system diversification, it provided insufficient weed suppression and failed to maintain yields comparable to mulching or manual weeding, indicating limited reliability as a standalone strategy [46].

More consistent benefits of intercropping have been reported in annual and short-cycle crops. In *Zea mays* L.–*Satureja hortensis* systems, increasing the proportion of *Satureja hortensis* significantly reduced weed biomass, while maize yields exceeded those of monocultures, demonstrating that species complementarity can simultaneously enhance weed suppression and crop productivity [76]. Similarly, *Cicer arietinum* L.–*Lallemantia iberica* (Stev.) Fisch. et Mey intercropping reduced weed pressure and mitigated yield losses under weedy conditions through greater plant density and canopy closure, supporting its role as a complementary cultural practice that reduces dependence on intensive weed control [52]. In vegetable–herb systems, intercropping *Capsicum annuum* L. with *Coriandrum sativum* achieved the strongest reductions in weed density and biomass among several agroecological treatments and produced the highest yields, outperforming mulching and botanical extracts, thereby confirming intercropping as a highly effective non-chemical strategy for sustainable production [38]. Additionally, living mulch systems further illustrate the potential of intercropping for weed suppression. Interseeding *Trigonella foenum-graecum* L. within *Coriandrum sativum* stands significantly decreased weed biomass and improved seed yield relative to untreated controls, particularly at higher mulch densities [39]. Nevertheless, weed control was not consistently maintained throughout the season, indicating that living mulch performs best when integrated with supplementary measures such as hand weeding. Collectively, these studies demonstrate that intercropping can substantially reduce weed pressure, enhance crop competitiveness, and improve yield stability without chemical inputs. However, its effectiveness varies with species combinations and environmental conditions, suggesting that intercropping should be implemented as part of integrated weed management programs rather than as a universal standalone solution.

6. Novel Approaches to Weed Control in MAP Cultivation

New approaches to weed management in MAPs, such as biological control, electronic, laser and fully autonomous or semi-autonomous robotic systems, as well as radiation-based methods, remain largely underexplored in the MAP sector. Although some practical experiences and preliminary reports suggest their potential applicability, robust experimental validation under controlled and field conditions is still lacking. The available evidence regarding the application of these novel weed control techniques in MAPs is limited, often fragmentary, and predominantly discussed in review papers rather than supported by comprehensive scientific studies providing clear assessments of their efficacy, selectivity, and economic feasibility [107,108].

Biological control involves the use of living organisms or their metabolic products, particularly plant pathogens, to suppress weed populations, but despite the demonstrated efficacy of fungal genera such as *Alternaria*, *Colletotrichum*, *Cercospora*, *Fusarium*, *Phoma*, *Phytophthora*, *Phomopsis*, and *Puccinia*, large-scale adoption is limited by biological, technical, economic, and regulatory constraints [109]. In addition, the specificity of MAP production systems, including small cultivation areas, high crop diversity, and strict quality requirements, further complicates the practical implementation and standardization of bioherbicidal agents under field conditions [35,110,111]. To date, research on MAPs has focused mainly on laboratory and controlled studies of bioherbicidal effects from essential oils, hydrolates, and extracts, with no field applications reported [112–114].

Allelopathy, the biochemical interaction between plants via secondary metabolites, offers a flexible and sustainable approach to weed management, but its practical adoption requires integration with crop management strategies, field validation, and potentially biotechnological enhancement to maximize its effectiveness [115]. Allelopathy studies in Petri dishes indicate that six cultivated and wild aromatic and medicinal plants (*Ocimum basilicum*, *Matricaria chamomilla* L., *Malva sylvestris* L., *Chelidonium majus* L., *Melissa officinalis*, and *Levisticum officinale* Koch.) can suppress germination and growth of scentless mayweed (*Tripleurospermum inodorum* (L.) Sch. Bip.). Extracts from these plants showed strong inhibitory effects, suggesting their potential as additional tools in integrated weed management [116]. Field studies on *Melissa officinalis* for seed production compared chemical herbicides (bentazon and fluazifop-p-butyl) with nonchemical control using mustard seed meal (1.5–3.0 t/ha). The higher dose significantly reduced weed number and biomass and yielded the most fresh herb, but seeds had reduced germination. The lower dose improved seed quality while maintaining weed suppression comparable to chemical treatments [15]. Despite promising results under controlled conditions, the practical application of allelopathy-based approaches in MAP systems is constrained by variability in field performance, difficulties in standardizing active compounds, and potential trade-offs between weed suppression and crop quality [117,118].

Similarly, although agricultural robotics has advanced significantly for conventional and specialty crops, no original research has yet investigated electronic, laser, or robotic weed control systems specifically designed or validated for MAPs. Evidence in MAPs is therefore currently absent, while existing knowledge is derived entirely from other cropping systems. In vegetables and other high-value row crops and specialty herbs, robotic weed management has progressed rapidly, with systems integrating computer vision, machine learning, and precision actuation technologies for targeted weed removal [119,120]. Examples include autonomous spot-spraying platforms that reduce herbicide use, as well as mechanical and laser-assisted weeding systems that achieve high detection accuracy and weed removal efficiency in row crops and precision agriculture contexts [121–123]. These developments illustrate the broader technological potential of robotic weed control in agriculture; however, their direct applicability to MAP systems remains untested and should therefore be interpreted as prospective rather than demonstrated. Moreover, the economic feasibility and technical adaptability of such systems in MAP cultivation remain uncertain, given the typically small-scale production, high plant density, and morphological diversity of MAP species, which may limit the efficiency of current detection and targeting technologies. Finally, radiation methods (e.g., gamma, UV, or electromagnetic) have been studied in MAPs primarily for their effects on plant bioactivity or phenolic content, rather than for in-field weed management [124–126]. Consequently, their relevance to weed management in MAP cultivation remains speculative, with no evidence supporting its practical applicability for in-field weed control in MAP systems, and requires substantial experimental validation before any agronomic relevance can be established [127]. Collectively, these emerging strategies remain at an early stage of development in MAP systems, with current evidence largely limited to controlled experiments or extrapolations from other crops [128]. Their practical implementation is constrained by biological, technical, and economic factors, highlighting substantial research gaps and the need for system-specific validation.

7. Chemical Weed Control

In addition to the abovementioned non-chemical weed management practices, herbicides are frequently included as reference treatments in experimental studies [6,32,36,43,45–47,49,50,63,67,70,72,82]; a brief overview is provided in Table 1 and Figure 4. However, the available literature addressing herbicide use in medicinal plants remains limited [12,37,62]. Regulatory restrictions on herbicide use in MAPs within the European Union have reduced the number of approved active substances, resulting in the progressive withdrawal or restriction of several herbicidal compounds from agricultural practice [129].

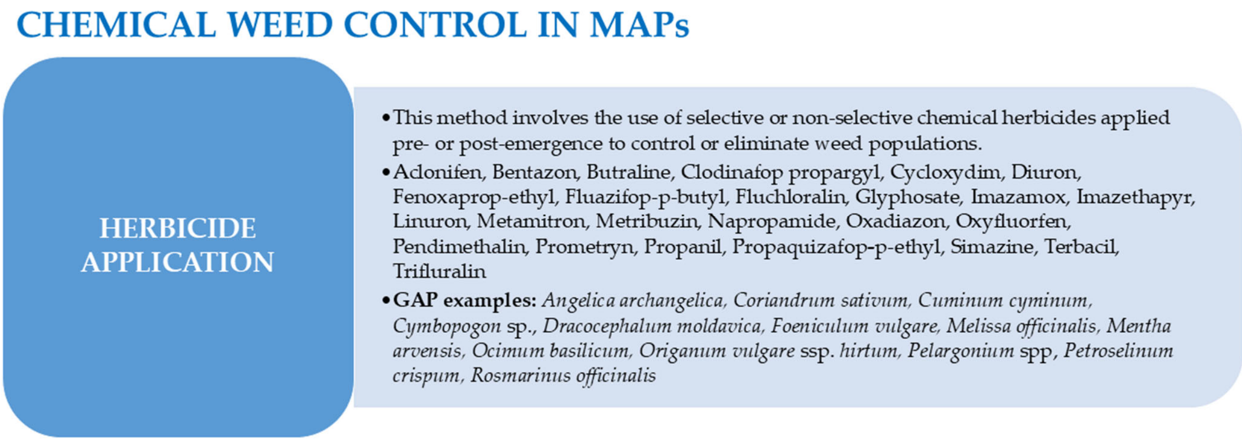

Figure 4. Overview of herbicide applications and examples of good agricultural practices (GAP) applied in medicinal and aromatic plant (MAP) cultivation.

7.1. Herbicide Efficacy in MAPs

Chemical weed management has been widely investigated as an effective strategy to protect slow-growing, long-duration medicinal and aromatic crops from yield losses due to weed competition. Field studies in *Coriandrum sativum* demonstrated that pre- and post-emergence herbicides such as pendimethalin and fluchloralin effectively suppressed weeds, maintaining seed and essential oil yields comparable to weed-free controls, while oxadiazon and propanil were selective but less efficient [36,37]. Similar benefits were observed in *Cuminum cyminum*, where integration of trifluralin or pendimethalin with wheat mulch reduced weed biomass, improved physiological traits, and enhanced seed and oil yield, with reduced herbicide rates (50–75%) combined with mulch providing comparable efficacy to full doses, suggesting a more sustainable approach [43]. In *Foeniculum vulgare*, pendimethalin-centered treatments, alone or integrated with hand weeding or mulches, ensured high weed control efficiency, low weed index, and improved economic returns [49,50].

Other studies in *Mentha arvensis*, *Ocimum basilicum*, *Pelargonium graveolens*, *Cymbopogon* sp., and *Angelica archangelica* confirmed that herbicides such as pendimethalin, diuron, oxyfluorfen, terbacil, and glyphosate effectively reduce weed density and biomass, producing yields comparable to manual weeding while generally maintaining essential oil quality [6,12,32,45–47,62,63,67,70,72,82]. Some herbicides, however, can influence the composition of bioactive secondary metabolites, highlighting the need to balance weed control efficacy with crop quality [32,47].

Overall, pendimethalin consistently emerges as a highly effective and economically viable option, and chemical weed management is often most successful when integrated with physical control measures or mulches, allowing for reduced herbicide rates, sustained season-long weed suppression, and minimal impact on essential oil yield and quality. These findings underscore the importance of optimizing chemical weed strategies in medicinal plant cultivation while considering crop safety, residue limits, and sustainability.

7.2. Herbicide Residues and Product Safety

However, when considering chemical weed management in MAPs, it is essential to account for herbicide and pesticide residues in raw plant material and essential oils [130]. Analyses of a wide range of plant samples have shown that pesticide residues can be present in a substantial proportion of commercially available herbal raw materials, with 50–70% of samples containing at least one active herbicide or fungicide, and in some cases, concentrations exceeding the maximum residue limits (MRLs) established for medicinal and culinary plants [131,132]. Similarly, large datasets on pesticide residues in essential oils indicate that while detections are generally low, certain products, especially those obtained by cold pressing, may contain residues above pharmacopoeial or legal limits, highlighting the need for targeted monitoring and regulatory compliance [133,134].

7.3. Regulatory Constraints and Practical Limitations

These findings indicate that chemical weed management strategies should consider not only effective weed suppression efficacy but also residue minimization in medicinal plant materials [135]. Regulatory frameworks such as the European Union MRLs and pharmacopoeial standards for medicinal plants require that pesticide residues do not compromise product safety and quality, emphasizing the importance of integrated approaches that combine reduced herbicide rates with physical weed control measures. It should be noted that, while the reviewed studies provide substantial information on herbicide efficacy, reports on early visual symptoms of phytotoxicity or plant recovery later in the growing season are scarce. In the European Union, the use of many herbicidal active substances in medicinal and aromatic crops is heavily restricted or withdrawn, further limiting the practical application of chemical weed control [81]. This highlights the importance of carefully evaluating potential crop stress and integrating chemical treatments, where allowed, with physical or cultural weed management measures to ensure crop safety, compliance with residue limits, and sustainable production.

In addition to the progressive withdrawal of active substances, a major limitation of chemical weed management in MAPs is that many herbicides commonly used in conventional agriculture are not registered or approved for use in these crops, further restricting their practical applicability. Moreover, the potential residual effects of pesticides applied to preceding crops are often insufficiently considered prior to the establishment of MAPs, which may pose risks for crop safety, product quality, and compliance with residue regulations. Despite their relevance, these issues remain largely underexplored, and there is a clear lack of targeted research addressing herbicide carryover and its impact on MAP cultivation.

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8. Summary and Perspectives

Current evidence clearly demonstrates that weed management remains one of the most critical constraints in MAP production, particularly during early growth stages when crop competitiveness is low. A wide range of non-chemical strategies, especially mulching, mechanical weeding, and crop diversification, have proven effective in reducing weed pressure while maintaining or improving yield and quality. Among these, mulching stands out as the most consistently reliable approach across diverse species and agroecological conditions, offering additional benefits for soil moisture conservation, nutrient use efficiency, and secondary metabolite accumulation. Mechanical and thermal methods provide valuable alternatives, particularly in organic systems, but their effectiveness is often limited by crop sensitivity, labor or energy requirements, and variable field performance. Diversification (i.e., intercropping and living mulches) contributes meaningfully to weed suppression and system sustainability, although its success is highly context-dependent and rarely sufficient as standalone solutions.

Chemical weed control continues to play a significant role, particularly in slow-growing or long-duration MAPs, where it often provides the most consistent and economical weed suppression. However, the number of registered herbicides for MAPs remains limited, and regulatory restrictions, especially within the European Union, are progressively reducing available active substances. In addition, increasing concerns regarding pesticide residues in medicinal raw materials and essential oils, as well as the risk of herbicide resistance from repeated use of the same chemical groups, place strong constraints on chemical weed management. These factors underscore the importance of integrated weed management strategies that combine reduced herbicide doses with physical, cultural, or mulching practices to achieve effective weed control while safeguarding product quality and regulatory compliance. In this context, the economic performance of different weed management strategies, including cost–benefit considerations and long-term profitability, should be regarded as a key factor guiding their practical adoption.

Looking forward, future research should prioritize the development of integrated, crop-specific weed management frameworks that account for species biology, growth dynamics and patterns, and intended end use of MAP products. There is a clear need for long-term, multi-site field studies evaluating combinations of non-chemical and low-input chemical strategies, with particular attention to residue dynamics, essential oil composition, and economic viability. Emerging approaches, such as bioherbicides, precision agriculture tools, and robotic weed control, remain largely unexplored in MAP cultivation systems but offer promising avenues for innovation. Advancing weed management in MAPs will therefore depend on interdisciplinary research, technological adaptation, and policy-aligned practices that support sustainable production while meeting the high quality and safety standards required for medicinal use.

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Abbreviations

The following abbreviations are used in this manuscript:

MAP	Medicinal and Aromatic Plants
MRL	Maximum Residue Limits
GAP	Good Agricultural Practices

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