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Review

Biomass from Allelopathic Agroforestry and Invasive Plant Species as Soil Amendments for Weed Control—A Review

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Abstract: Effective weed management faces increasing legislative restrictions for the use of herbicides due to their toxicity and environmental persistence. In addition, the linear increase in resistant weeds threatens to render authorized herbicides useless. In a post-herbicide era, under the IWM strategy, allelopathy can play a relevant role since many plants can produce a variety of allelochemicals with different structures and modes of action, capable of inhibiting the germination and growth of different weed species. Inspired by green manuring with cover crops, the use of allelopathic biomass from weeds, invasive species, residues of forestry plantations, and other abundant wild plants has some advantages over green manures grown in situ or other alternatives such as applying plant extracts or essential oils. Beyond the ecosystem services provided by green manures, the potential use of allelopathic biomass offers extra opportunities for the science and practice of holistically integrated weed management because (i) the investment of resources and time for producing cover crops would be alleviated, and (ii), new use of agroforestry residues and a sink for harmful weed biomass is provided. In this review, we compile the current knowledge of those allelopathic species whose biomass, used as soil amendment, effectively controlled weeds. In addition, the complex allelopathic processes underlying the effectiveness of cover crops and allelopathic biomass used as green manures for weed control are revisited.

Keywords: allelochemicals; allelopathic biomass; DNSH; green manure; IWM; plant-based approaches; phytotoxicity; synergisms

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1. Introduction

Weeds dramatically limit the productivity of agricultural soils, competing with crops for agroecosystems' resources. Weed control represents a significant percentage of the budget invested in agriculture and a considerable investment of time and labour [1]. Many pesticides have been developed in the last century, notably increasing crop yields. Their production and application entail a significant economic expense the farmer cannot always afford. However, one of the main drawbacks of synthetic herbicides is their irrational use and misapplication, which can cause severe damage to the agroecosystem. They can reduce soil fertility due to their potential toxicity even at low concentrations of active principles. In addition, their excessive use has increased the contamination of soils, groundwater, and surface water, contributing to the deterioration of natural ecosystems [2,3]. It has also been argued that some active ingredients of synthetic herbicides are incorporated into food chains, bio-accumulating, and bio-magnifying, posing a risk to animal and human health [4].

Consequently, European legislation eliminated several products or active ingredients considered harmful to the environment or health from the market (EC 1107/2009, EU 540/2011), often with additional restrictions by country and region (e.g., RD 1311/2012, and RD 971/2014 from Spanish legislation). Currently, amid an arduous international controversy surrounding the safety of glyphosate (the most widely used herbicide worldwide in agriculture, parks and gardens, and control of invasive species) [3,5], glyphosate-based products are in a moratorium period of use granted by the EU, which was scheduled to be withdrawn in December 2023 by mandate of the European Parliament in 2017. However, due to the lack of alternatives, a new 10-year moratorium is already a fact, recently approved by the EU. The number of authorised herbicide active ingredients is expected to decline in the coming years.

Last but not least, the linear increase in resistant weeds, coupled with the lack of new mechanisms of action (MoAs), threatens to render all existing herbicides useless by 2050 [6]. More than 500 weed biotypes have developed resistance to 21 of the 31 known herbicide sites of action and 164 different herbicides [7,8], and no herbicides with actual new molecular targets have been commercialised in the last 30 years [9]. All these issues have increased social concern about the use of synthetic herbicides, thus increasing the interest in the development of new active principles based on the diversity of natural plant products with new MoAs, in addition to new bio-inspired strategies to control weeds in an IWM (integrated weed management) strategy [10].

Complementary tools for IWM include allelopathic cultivars of cash crops and cover crops for consumption or other uses like green manuring or mulching [11]. Notably, the increasing use of cover crops for outcompeting weeds has become the bridge for the greater incorporation of IWM across all cropping systems [10]. In recent years, some studies explored the allelopathic biomass already available from the agroecosystem for its use as a soil amendment for weed control, including the residual biomass of cultivated or invasive species. This review aims to compile the current knowledge of those allelopathic species whose biomass used as plant-based soil amendment effectively controlled weeds, and the key allelopathic processes underlying their effectiveness are revisited.

2. Allelopathy and Allelochemicals

Using allelopathic plants with herbicidal potential has led to growing interest in the scientific community [12]. The phenomenon of allelopathy refers to "any direct or indirect effect of a plant on other plants through the release of bioactive compounds (called allelochemicals) by volatilisation, leaching, root exudation, or decomposition of plant residues" [13]. In 1996, the International Allelopathy Society extended the definition of allelopathy to "any process involving secondary metabolites produced by plants, algae, bacteria, and fungi that influences the growth and development of agricultural and biological systems". Allelochemicals are complementary bioactive metabolites such as glucosinolates, phenolic compounds, terpenoids, alkaloids, and hydroxamic acids widely distributed throughout plant organs [14]. They have significant adaptative roles in plant communication and defence against biotic and abiotic stressors [13]. The chemical variability of allelochemicals is vast, and many have been reported to exert phytotoxic effects on different crops and weed species. They present advantages over traditional herbicides because they are a priori eco-friendly, readily biodegradable with a short half-life, and with new molecular targets different from synthetic herbicides [15] due to their outstanding structural diversity.

Plant–plant allelopathy affects various physiological processes such as germination, development, phytohormonal activity, plant water balance and stomatal function, photosynthesis, respiration, and synthesis of specific biomolecules [16–19]. Most of the MoAs of allelochemicals are not fully understood, but the best-known and studied differ markedly from the approximately 30 currently known modes of action associated with synthetic herbicides [15]. Allelopathy has a decisive influence on the functioning of natural ecosystems and agroecosystems, modifying and inhibiting the development of wild plant species, weeds, and crops. Allelopathic compounds are gaining relevance and interest as sustainable and beneficial alternatives to traditional herbicides. Such diversity of bioactive natural compounds offers hope for discovering ecological herbicides that are harmless to crops but toxic to weeds without forming hazardous residues [14]. However, it must be considered that allelopathic compounds' herbicidal capacity and efficacy depend on variables such as the release mechanism, chemical structure, stability and persistence in the environment once dispersed, or how they interact with other organisms in the agroecosystem.

Some of the most studied allelochemicals are sorgoleone and momilactones. Sorgoleone is an excellent example of a natural herbicide. Its efficacy as a herbicide has been compared to synthetic herbicides in commercial use [20]. This allelochemical is secreted by sorghum, and it can disrupt mineral and water uptake and affect the photosynthesis of target plants. Sorgoleone has been shown to directly influence plant growth in laboratory, greenhouse, and field studies.

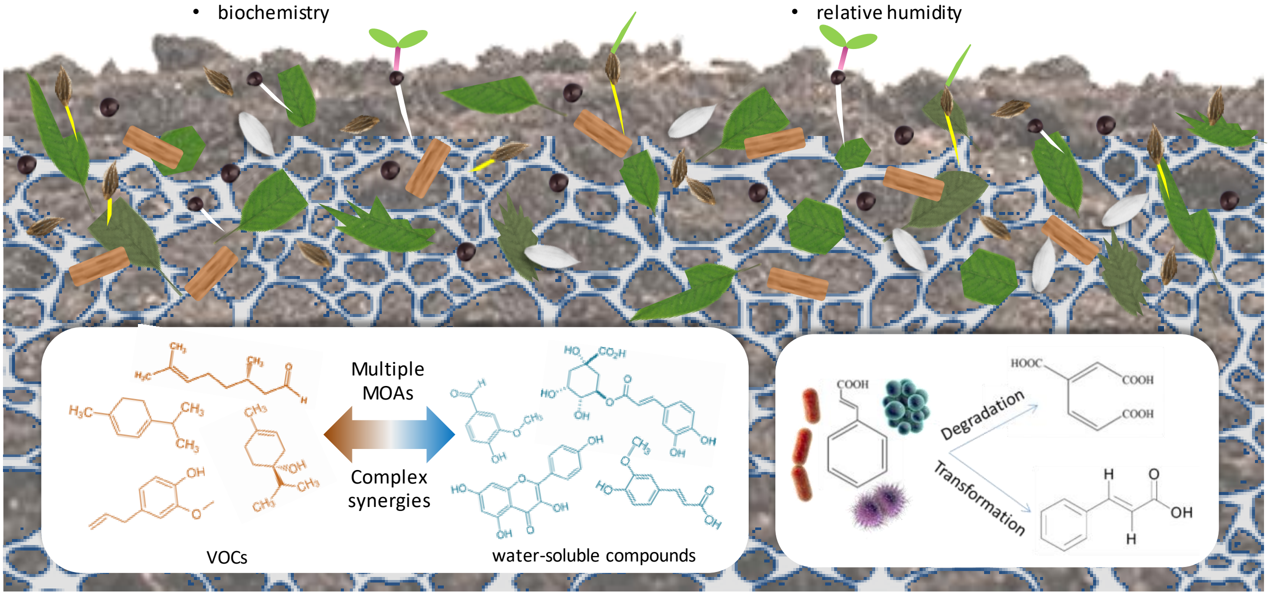
On the other hand, momilactones (M), especially MA and MB, were recognized as potent rice-derived allelochemicals. In particular, they exhibited substantial allelopathic activity against problematic weeds (e.g., *Echinochloa crus-galli* (L.) Beauv., *Monochoria vaginalis* (Burm.f.) C. Presl. ex Kunth, *Solidago altissima* L.) [21]. However, none of them has been successfully developed as a natural herbicide. This situation may be due to limitations in their isolation and purification from plant sources and costs. Environmental stability is also a limitation because allelochemicals in soil can be inactivated by degradation, oxidation, binding to other substances, or other soil factors including electrical conductivity, osmotic pressure, microorganisms, and adsorption to soil particles [22,23].

Although allelochemicals have been shown to have phytotoxicity individually or in isolation, it should be highlighted that complex mixtures of various compounds of different chemical classes generally mediate allelopathy. Therefore, due to additive or synergistic effects, allelochemicals with low activity when acting alone may be more critical and have higher phytotoxicity in a mixture [22]. The concept of synergy refers to the phenomenon by which the joint effect of two or more factors (in this case, allelochemicals) is increased or enhanced, achieving higher results than the sum of the effects of each separately. This phenomenon has been evaluated in just a few studies to date. For example, synergy phenomena between different monoterpenoids were observed in vitro by Vokou et al. [24], revealing significant results in the case of carvacrol with *p*-cymene and γ-terpinene on plant elongation and combining geraniol and neomenthol on germination and elongation. Regarding root exudates, MB, 5,7,4-trihydroxy 3,5-dimethoxyflavone, and 3-isopropyl-5-acetoxycyclohex-2-enone were shown to have more powerful effects together than individually [25]. Pardo-Muras et al. [26] reported that binary mixtures of the essential oils eugenol, verbenone, terpinen-4-ol, α-terpineol, and linalool produced synergistic inhibitory effects on germination and early growth of *Amaranthus retroflexus* L. and *Digitaria sanguinalis* (L.) Scop. Dias and Moreira [27] observed that the leachates of *Cistus ladanifer* L. leaves enhanced the phytotoxicity of several volatile organic compounds (VOCs) on the germination of *Trifolium subterraneum* L. Recently, Pardo-Muras et al. [28] stated that the multiple synergistic interactions among VOCs and water-soluble compounds (phenolic acids and flavonoids) at their natural concentrations and proportions were crucial to the weed control exerted by *Cytisus scoparius* (L.) Link. foliage used as a soil amendment. These powerful interactions have promising potential for combining minimal quantities of compounds from different natures, chemical classes, and MoAs to increase herbicide efficacy and minimize resistance development. Therefore, a better understanding of allelochemical production associated with plant defence strategies may allow us to better protect and manage developing crops, control the spread of invasive species, preserve native plant stands, and create strategies to develop and apply allelochemicals as new pesticides [29], taking advantage of these synergistic interactions for extra efficacy.

Many studies that have been published so far focused on using aqueous extracts or essential oils [30–32] to apply this potential synergy based on 'the cocktail' [33] of compounds. However, although they are effective immediately upon application, they have disadvantages. For instance, their fate in the agroecosystem is usually uncertain. Noteworthy, most of the isolated natural compounds, aqueous extracts, and essential oils that are effective in the laboratory as pre- or post-emergence herbicides, once in the field, have little or no effectiveness due to their dilution, volatility, short life, instability or rapid degradation by microorganisms or other interactions with the soil (Figure 1) [22]. Consequently, these application forms do not achieve a sufficiently long-lasting pre-emergence effect in controlling the gradual germination of seeds in an actual weed seed bank or the growth of weeds that have managed to germinate. Therefore, there remains a need for new controlled-release formulations that are guaranteed to be effective in the field. Thus, allelopathy remains a largely untapped source of active compounds for potential use to control weeds [30].

Allelopathic biomass or green-manure variables:
- species
- growth stage
- C/N ratio
- physiological status
- biochemistry

Meteorological covariables:
- temperature
- precipitation
- evaporation
- light intensity and quality
- relative humidity



The fate of allelopathic compounds depends on:
- leaching from plant tissues
- transport in soil water
- emanation from plant tissues
- diffusion in soil pores
- soil retention, adsortion
- degradation
- transformation in active or inactive derivatives
- chemical interactions (antagonistic or synergistic)

Soil covariables:
- organic matter
- cation exchange capacity (CEC)
- pH
- EC
- water retention capacity
- granulometry
- porosity
- organism (microbiota and mesofauna)

Figure 1. Processes involving the effectiveness of allelopathic plant-based approaches for weed control (original design by the authors). For allelopathic cover crops incorporated into the soil as green manures, or biomass from agroforestry allelopathic species used as soil amendments for weed control, a variety of volatile (VOCs) and water-soluble phytotoxic compounds are progressively released from the tissues of crushed and buried leaves, flowers, stems, and thin branches. This cocktail of allelopathic compounds provides multiple modes of action (MoAs) capable of inhibiting the germination and early growth of weeds. The complex synergistic interactions occurring among compounds of different chemical classes, present at very low individual concentrations in the soil matrix, could explain the effectiveness of allelopathic biomass for weed control. Soil microorganisms can degrade the allelopathic compounds, metabolize them into other bioactive molecules, or even produce their own allelochemicals. The transformations that allelochemicals undergo in the soil through leaching, adsorption, transformation, or degradation, besides the multiple variables affecting such processes, are also summarized following Kobayashi [22] and Soltys et al. [15].

3. Allelopathic Cover Crops for Weed Control

The use of allelopathic crops for weed management in agroecosystems has been widely studied and implemented, either by (i) including them in rotational sequences, (ii) intercropping near a cash crop, (iii) cover cropping as living or dead mulches or (iv) crop residue incorporation into the soil. A large number of cultivars are known to possess allelopathic properties, most of them belonging to the families Asteraceae (e.g., *Helianthus annuus* L., *Artemisia absinthium* L., *Carthamus tinctorius* L., *Cichorium intybus* L., *Cynara cardunculus* L., and *Lactuca sativa* L.) and Poaceae (*Oryza sativa* L., *Secale cereal* L., *Triticum aestivum* L., *Sorghum* spp., *Hordeum vulgare* L., and *Avena sativa* L., among others).

Brassicaceae (e.g., *Brassica juncea* (L.) Czern., *Brassica oleracea* L., and *Capparis spinosa* L.), and Fabaceae (e.g., *Medicago sativa* L., *Phaseolus vulgaris* L., *Pisum sativum* L., and *Vicia faba* L.) are also well-represented families [11].

CAP (EU Common Agricultural Policy) greening and, currently part of the 'EU Green Deal', the 'Farm to Fork Strategy' [31] have rekindled scientific and practical interest in cover crops in replacing winter fallow, in addition to profiting from their multiple ecosystem services. More related to this review, green manuring consists of using fast-growing crops cut and buried in the same place of sowing. This practice improves soil structure and physicochemical balance, activates the microbial population, and enriches the soil with mineral nutrients [32]. Moreover, it helps reduce evaporative water loss, fertilizer inputs, and greenhouse gas emissions [34,35].

If the green manure is also allelopathic, the extra ecosystem service of weed control can be provided [36]. Disseminated into the soil by leaching and volatilization, water-soluble and volatile compounds released by the allelopathic green manure can act concomitantly during the decomposition of plant material into the soil (Figure 1) [28,37]. As allelopathic residues slowly release the phytotoxic compounds into the environment, this leads to prolonged herbicidal effects. Water soluble compounds are leached after incorporation into the soil early, and volatile compounds are sequentially emitted to the soil pores in the long term [33]. Some authors, such as Yenish et al. [38], have studied the duration of allelopathic residues of rye and found that half of them disappeared after 105 days. Still, the phytotoxic compounds took another 60 days to degrade.

Contrary to the general observation that phenolics and terpenoids lose bioactivity when applied to agricultural soil, allelochemicals released progressively and directly by plant residues into the soil exceeded the expected results [26,28]. The microbiota can transform allelochemicals (Figure 1) so that new products with more significant biological activity than their precursors can be originated [39]. Pardo-Muras et al. [28] observed that the soil factor enhanced the synergistic interactions among VOCs and water-soluble compounds. Also, VOCs and aqueous extracts have shown some complementarity, with weed germination being more sensitive to water-soluble compounds and early growth to volatiles [33].

Recent reports dealt with green manuring for weed control under greenhouse and field conditions. For instance, Masilionyte et al. [40] conducted a 6-year field study on the herbicidal potential of different allelopathic cover crops cultivated for green manure. These authors found that *Sinapis alba* L. combined with *Fagopyrum esculentum* Moench. exerted a more significant reduction in the number and yields of weeds than *Lupinus angustifolius* L. in a mixture with *Raphanus sativus* L. In another study, *Vicia faba* incorporated into the soil as green manure inhibited the density and biomass of dicotyledonous (*A. retroflexus*, *Chenopodium album* L. and *Solanum nigrum* L.) and monocotyledonous (*D. sanguinalis* and *Cyperus rotundus* L.) weeds by up to 70% and 78%, respectively, in a maize crop, thus reducing the need for post-emergence herbicides [36]. Alonso-Ayuso et al. [41] conducted a field trial to study the effect of replacing winter fallow with barley (*H. vulgare*) or vetch (*Vicia sativa* L.) on weed control. In general, cover crops had more positive effects on weed density, weed diversity, and the seed bank than winter fallow, with barley achieving better weed control than vetch in winter and early spring. In 2021, Rugare et al. [42] carried out a greenhouse trial to evaluate the effect of eight green manure cover crops on the germination and seedling development of goose grass (*Eleusine indica* (L.) Gaertn.) and blackberry weed (*Bidens pilosa* L.). All residues significantly affected weeds' seedling emergence, dry weight, and vigour indices. Liu et al. [43] observed that using *Astragalus sinicus* L. as green manure significantly reduced the germination and growth of *E. indica*; on the contrary, it favoured the growth of maize in a pot experiment.

Some synergistic effects between allelopathic cover crops have been reported. For instance, the mixture of *S. cereale* and *Trifolium squarrosum* L. produced more significant inhibitory effects on the germination and growth of *D. sanguinalis* than the monocultures of each species [44]. The continuous and sequential release of allelochemicals during decomposition and the joint action of their different MoAs can make mixed cover crops effective against a higher number of species in the weed seed bank, even those biotypes that have developed resistance to synthetic herbicides. However, as explained, the mixture of species can even ameliorate the results of allelopathic green manuring since intercropping can favour the production, release, and activation of compounds into the soil [44].

Soil-incorporated organic matter also exerts physical weed control [45] by acting as a barrier or competing for space and nutrients during growth in the case of living green manures [10,40]. For all these reasons, allelopathic green manures have become valuable tools in IWM, with agronomic, environmental, and economic advantages compared to the application of isolated allelochemicals, aqueous extracts or essential oils.

4. Use of Allelopathic Agroforestry and Invasive Plant Species as Soil Amendment for Weed Control

Although effective, growing allelopathic crops for mulch or green manuring as part of an IWM strategy takes up time and space in the farm crop plan. It requires an investment and sacrificing a productive period from which no harvest is obtained.

However, allelopathic biomass is already available in the agroecosystem. Why not use it for green manuring? Some wild plants, invasive species, weeds, and forest residues can release allelochemicals into the environment. Sometimes, this biomass is found in the immediate vicinity and peripheries of most operations and is, therefore, easily accessible to the farmer [46]. Besides providing some of the benefits of allelopathic green manures grown on farms, this practice could also increase the efficiency of the agricultural system by reducing the need for agrochemicals and other inputs as much as possible. Noticeably, in those agricultural scenarios where the practice of green manuring is established, the practical know-how is well internalised by farmers, and the machinery required for its implementation (forage choppers, spreader wagons, manure spreaders, disc harrows, etc.) is usually available for community use through agricultural cooperatives.

Moreover, using available allelopathic biomass would provide a sink for specific residues of nearby forest plantations and biomass of invasive plants removed in local control initiatives. But how can farmers access these residues and surplus allelopathic biomass derived from various activities in the agroforestry sector? Implementing this plant-based strategy, unlike green manuring from cover crops, would require the establishment of new local or regional cooperation initiatives between neighbouring actors of the agroforestry sector, which may represent a bottleneck. Nevertheless, the availability of biomass from short-chain suppliers could become coordinated with the activities of nearby companies that produce essential oils, timber, paper pulp, or bioenergy. Raw materials for these companies are supplied by forest plantation owners, forest holdings, or commonwealth forests, from the industrial activity of which vast amounts of residual biomass are produced. Usually, such byproducts consist of no more and no less of allelopathic valuable biomass for weed control in agricultural fields. Biomass collection, transport, and delivery for other circular economy purposes are known practices and are often already integrated into modern forestry, both small-scale and state-wide, in a joint environmental endeavour within the International Family Forest Alliance. It would suppose a further step forward in providing an extra service to the agricultural sector.

Of course, careful biomass management of harmful and invasive weeds should be carried out to avoid the accidental spread of propagules. In general, allelopathic biomass is more effective in controlling weeds during early flowering, well before the formation or maturation of seeds, because the concentrations and diversity of allelochemicals are usually higher in this phenological stage [30]. Post-harvest treatments by chopping, grinding, and drying would be required to destroy any vegetative propagule of invasive weeds before application to the agricultural soil to prevent resprouting [46].

In contrast to aqueous extracts or essential oils from aromatic plants assayed as bioherbicides, using entire plant tissues provides the "natural envelope" without needing encapsulation, stabilizers, or adjuvants. The phytotoxic cocktail contained in plant tissues is progressively released into the soil at low concentrations and natural proportions of allelopathic compounds, thus attaining the duration and dynamics that provide weed management by cover crop green manuring, as referred above.

The following subsections explore numerous examples from the scientific literature, in alphabetical order, where the biomass of different allelopathic species available from the agroecosystem worldwide has achieved significant weed control.

4.1. *Acacia* spp.

Acacia spp. is a widespread worldwide genus in the family Fabaceae with high invasive potential. More than 20 *Acacia* species have been confirmed invasive globally, including Europe and Mediterranean countries [47]. They spread rapidly from colonized areas because of their N-fixing capacity, allelopathic potential, and ability to germinate and sprout after fires, resulting in communities with very limited biodiversity [48].

There is evidence of the allelopathic effects of the invasive species *Acacia dealbata* Link. and *A. longifolia* (Andrews) Willd. through the exudation of phenolic compounds into the surrounding environment and by chemically hindering the settlement of surrounding plants [49,50]. Also, VOCs released from *A. longifolia* flowering foliage are phytotoxic to native species [51]. Residues of both species were tested for their herbicidal potential by Souza-Alonso et al. [52]. The results obtained in pots revealed that the soil amendment of *A. dealbata* applied at 3% significantly reduced the emergence of some dicotyledonous weeds like *A. retroflexus* and *Portulaca oleracea* L., shifting dominance towards the monocots. The allelopathic compounds were found in higher concentrations in the first days after biomass application and decreased dramatically. Field experiments denoted significant but moderate phytotoxic effects of *A. dealbata* biomass on dicot weeds. Recently, Lorenzo et al. [53] observed that incorporating *A. dealbata* residues into the soil four months before planting corn controlled some dicot weeds and alleviated the need for starting fertilizers.

4.2. *Ageratina adenophora (Spreng.) R. M. King & H. Rob*

Ageratina adenophora (syn. *Eupatorium adenophorum* Spreng., see Section 4.10), commonly named crofton, is a perennial weed in the Asteraceae family native to Central America, which has invaded more than 30 tropical and subtropical countries worldwide [54]. This species synthesizes and releases many allelochemicals to the environment, mainly terpenoids, flavonoids, and phenolic derivatives [55]. Among them, DTD (4,7-dimethyl-1-(propan-2-ylidene)-1,4,4a,8a-tetrahydronaphthalene-2,6(1H,7H)-dione) and HHO (6-hydroxy-5-isopropyl-3,8-dimethyl-4a,5,6,7,8,8a-hexahydronaphthalene-2(1H)-one) have shown a more significant herbicidal effect [56]. These allelochemicals were able to inhibit the germination and growth of *Lolium perenne* L. [57], *T. aestivum* [58], and *Zea mays* L. [59]. In rice, the herbicidal activity was found to consist of metabolic alterations due to an increase in abscisic acid and a decrease in indole-3-acetic acid, causing cell damage and inhibiting normal plant development [60].

Jiao et al. [54] observed that incorporating the non-composted leaves and shoots of *A. adenophora* inhibited ryegrass growth, decreased plant nutrient uptake, and negatively affected soil enzyme activities, microbial biomass, and biodiversity under greenhouse conditions. However, in this case, the phytotoxicity may also be detrimental to the crops, so a better knowledge of its application in agricultural use is required. Notably, phytotoxicity was greatly reduced when the biomass underwent a composting process. Although still valuable as a fertilizer, the composted biomass did not provide weed control [54]. Such inactivation could be due to the thermolability that characterizes most allelochemicals, which must be considered in processing any allelopathic biomass for weed control.

4.3. *Ailanthus altissima (Mill.) Swingle*

Also known as the tree of heaven, *A. altissima* is native to Southeast Asia and one of Europe and North America's most invasive plant species due to its high environmental tolerance and rapid spread. Such invasiveness is probably caused by the production of allelochemicals, mainly alkaloids, terpenoids, steroids, flavonoids, phenolic derivatives and quassinoids [61,62], including the quassinoid compound called ailanthone [63]. Isolated ailanthone has shown pre- and postemergence herbicidal activity on *A. retroflexus*, *Setaria glauca* (L.) P. Beauv, *Echinochloa crusgalli* (L.) P. Beauv., and *Z. mays*, although it showed a high degradability by microbial activity (lasting 3 to 5 days) [64].

The essential oils and aqueous extracts of *A. altissima* have been extensively tested for weed control in pre- and post-emergence tests [65]. Using biomass mixed with soil, two grams per pot of *A. altissima* root bark significantly inhibited seedling emergence and reduced cress shoot (*Lepidium sativum* L.) yield to 5% of the control in a greenhouse trial [63]. However, root bark toxicity disappeared some weeks after the tissues were incorporated into the soil, probably due to microbial degradation. Studies so far are scarce, but *A. altissima* biomass has the potential to be used as a natural herbicide in a circular economy strategy coupled with initiatives to control invasive woody species [50].

4.4. *Amaranthus* spp.

The genus *Amaranthus* accomplishes different species of highly competitive annual weeds from the family Amaranthaceae, worldwide distributed in tropical, subtropical and temperate regions. *Amaranthus retroflexus* L., *A. viridis* L., and *A. palmeri* S. Wats. are worse weeds that can resist the available herbicides [8,66]. Some species of the genus, mainly *A. hypochondriacus* L., *A. caudatus* L., and *A. cruentus* L., are cover crops very appreciated in Central and South America for the high nutritional value of their small and abundant seeds.

Signs of phytotoxicity have been reported for some *Amaranthus* species. Carvalho et al. [67] evaluated the phytotoxic effects of ethanolic leaf extracts from *A. spinosus* L., *A. viridis*, *A. deflexus* L., *A. hybridus* L., and *A. retroflexus* on *L. sativa*. The extracts, which were rich in organic acids, carotenoids, and steroids, inhibited germination in a dose-dependent manner and reduced the early growth of seedlings. Other specific effects were increased mitotic events, chromosomal alterations, and condensed nuclei in exposed cells. In another work, Bakhshayeshan-Agdam et al. [68] identified twenty compounds from the phytotoxic aqueous extract of *A. retroflexus*, docosane, triacontane, silane, and ethoxytrimethyl being the most relevant compounds with reputed allelopathic activity. The crude extract (ethanol: water) of *A. cruentus* tested in vitro was shown to inhibit the germination of tomato, cabbage, and the weed species *C. bonariensis* seeds [69].

Cover crop residues of *A. hypochondriacus* applied on the soil surface and then incorporated into the soil were applicable in radish, onion, and carrot crops to control the emergence and growth of *Simsia amplexicaulus* (Cav.) Pers., *Eleusine indica* (L.) Gaertn, *Pennisetum clandestinum* Hochst. Ex Chiov., and *Cynodon dactylon* (L.) Pers. [70].

Also, the incorporation of *A. palmeri* into the soil inhibited the growth of subsequent plantings like sorghum, onion, carrot, and its own plant, and the phytotoxicity lasted up to 16 weeks. Water soluble compounds and volatiles were argued to underlie the phytotoxicity of *A. palmeri* ([66] and references therein). *A. palmeri* being a new invasive weed species in summer crops in Europe [8], with extreme fecundity, fast growth, and competitiveness, the potential use of its biomass and the elucidation of its allelopathic nature deserves to be studied.

4.5. *Artemisia* spp.

Artemisia constitutes a broad genus of shrub species with rhizomatous growth and wide environmental tolerance found in northern temperate regions [71]. Some species of the genus present invasive behaviour associated with releasing allelochemicals by the glands on the surface of leaves. In the US, this shrub is considered a problematic weed in agricultural fields, although different species of *Artemisia* affect crops worldwide [71].

Artemisia species (e.g., *A. annua* L., *A. arborescens* L., *A. campestris* L., *A. gracunculus* L., *A. maritima* L., *A. scoparia* Waldst. & Kit., *A. vulgaris* L.) represent rich sources of various types of allelochemicals. For any plant species, differences in bioactive compounds' qualitative and quantitative composition could be correlated with environmental abiotic and biotic factors, ecotype, geographical origin, climate, plant age, soil, vegetation stage, plant part, and harvesting season [72]. The chemical composition of the aqueous extracts and essential oils of the different species of the genus, as well as the phytotoxic effect of their main constituents, is collected and detailed in Ivănescu et al. [73]. Artemisinin, a sesquiterpene lactone, is the most studied because it is part of the artemisinin-based combination therapies used in the treatment of malaria, whose bioactivity and structure have attracted much interest as a potential bioherbicide [74].

Some studies have demonstrated the herbicidal potential of the aqueous extracts or essential oils of numerous members of the *Artemisia* genus in various field settings [73]. Otherwise, studies on biomass used as a soil amendment are scarce; only Delabays et al. [74] reported that soil-incorporated leaves of *A. annua* (containing 0.81–0.22% artemisinin) inhibited the growth of *Z. mays*.

Given the high growth rates of *Artemisia* spp. and availability of biomass, besides the reported bioactivity of artemisinin, species of the genus are good candidates to be explored as allelopathic biomass used as a soil amendment for weed control. However, before being implemented, field experimentation and a deep assessment of the side-effects on crops and soil micro- and mesobiota are needed.

4.6. *Cassia* spp.

The genus *Cassia*, belonging to the Fabaceae family, comprises species that synthesize and release bioactive secondary metabolites with phytotoxic potential such as afzelin (kaempferol-3-rhamnoside) and its derivatives, anthraquinones, and phenolic acids [75]. Its herbicidal capacity has been demonstrated mainly by aqueous extracts under in vitro conditions. *Cassia* spp. extracts have shown phytotoxicity on *Z. mays* [76], *Brassica campestris* L. [77], and weed species such as *C. album*, *Melilotus alba* Medik, *Nicotiana plumbaginifolia* Viv. [78], and *Pathenium hysteophorous* L. [79]. The powder preparations of *C. tora* L. and *C. uniflora* Mill. have demonstrated herbicidal activity on the germination and growth of *P. hysterophorous* [79]. Hussain et al. [80] found that the mulch and incorporation into the soil of *C. angustifolia* M. Vahl. residues affected the germination and seedling growth of maize, rice, sorghum, wheat, and the weed species *Avena fatua* L., *Dactyloctenium aegyptium* (L.) Wild., *Echinocloa colona* (L.) Link., *P. minor* and *Sorghum halepense* (L.) Pers. This genus could present a potential for application in weed control; however, extra field trials are still needed to understand the allelopathic underlying mechanisms for practical application.

4.7. *Cistus ladanifer* L.

Cistus ladanifer is an endemic shrub species of the Iberian Peninsula, adapted to the Mediterranean climate, constituting a shrubland known as "jaral". The allelopathic character of *C. ladanifer* is the cause of the low plant richness characterizing these ecosystems [81].

Many allelopathic compounds responsible for these phytotoxic effects have been identified, mainly consisting of terpenes such as α-pinene, camphene, viridiflorol, ledol, and oxocativol [82,83]. Also, phenolic acids like gallic acid and flavonoids such as apigenin, kaempferol, quercetin, and ellagic acid have been characterized [84]. These allelochemicals have demonstrated their herbicidal activity, especially on seed germination in herbaceous species, being applied as aqueous extracts [85], essential oils [82,83] or as allelopathic biomass added to soil [81]. Dias and Moreira [27] suggested that the simultaneous presence of water-soluble compounds and VOCs might enhance the bioactivities of the metabolites released by *C. ladanifer*, maybe through chemical modifications. In addition, these compounds also present auto-phytotoxicity, which can be explained as a type of population regulation towards adverse climatic situations [81]. In the study carried out in 2012 by Verdeguer et al. [82], the phytotoxic effects of the essential oils of *C. ladanifer* were tested against *Amaranthus hybridus* L., *P. oleracea*, *C. album*, *Conyza canadiensis* (L.) Cronq., and *Parietaria judaica* L. The effects obtained were selective, observing an absolute inhibition of *C. canadiensis* and *P. judaica* germination in all tests and significant effects on *P. oleracea*, although it did not affect *C. album*. Growth inhibition of seedlings was also observed, although not as significant. In the experiment conducted by Gallego et al. [81], the results were similar, observing powerful phytotoxic effects of the leaf litter of *C. ladanifer*, on *Cytisus multiflorus* (L'Hér.) Sweet, *Lavandula stoechas* L., and *Cistus salviifolius* L. This study concluded that, in its natural habitat, over time, the degradation of the *C. ladanifer* litter provides a constant supply of phytotoxic allelochemicals, hindering the development of other species that could compete for scarce resources.

4.8. *Cytisus scoparius* (L.) *Link*

Cytisus scoparius, known as the Scotch broom, is a legume species endemic to the Atlantic zone. Its invasive nature generated critical environmental problems in many countries in America, Asia, and Oceania [86], and it is significantly harmful in South Africa [87,88]. In 2012, Grove et al. [89] argued allelopathy as the possible mechanism for *C. scoparius* to compete intensely with native vegetation, thus reducing seedling recruitment and growth of understory species in open forest areas.

In 2018, Pardo-Muras et al. [30] demonstrated that *C. scoparius* released allelochemicals into the environment with herbicide potential. It was shown that the fresh plant material naturally produced and emitted low amounts of VOCs like linalool, terpinen-4-ol, α-terpineol, and verbenone [30] and water-soluble compounds like *p*-coumaric, caffeic, trans-cinnamic and ferulic acids, among others [86], capable of inhibiting the germination and early growth of *A. retroflexus* and *D. sanguinalis*. In the early flowering season, *C. scoparius* had the highest concentration of phytotoxic compounds. Applying flowering foliage as soil amendment controlled the emergence of *D. sanguinalis*, *Convolvulus arvensis* L., *P. oleracea* and *A. retroflexus*, with a notable control of weed yields [37]. Otherwise, it was innocuous to maize or even stimulating, probably due to the N fertilising effect. As explained above, the allelochemicals of *C. scoparius* have shown powerful synergies, preferably at their naturally low concentrations and proportions, which are even enhanced by the soil factor [26,28]. This knowledge makes this species highly appropriate to be used as allelopathic biomass for field weed control [46].

4.9. *Eucalyptus* spp.

The genus *Eucalyptus* comprises tree species belonging to the Myrtaceae family, with ca. seven hundred species originating from Oceania. Nevertheless, many are widely distributed worldwide and considered invasive species in Africa, America, Asia, and Europe. The main reason for their spread was their cultivation to exploit by the paper and timber industries, besides the obtention of essential oils and bioenergy as secondary uses, but fast growth and allelopathy have also been argued for their invasiveness.

Eucalyptus species have been shown to exert many bioactivities by a wide range of biologically active compounds [90–92], including allelopathic activity [93]. The chemical compositions of the aqueous extracts and essential oils have been described, with phenolic compounds and terpenoids being generally identified, respectively [33,90,91,94–96]. Puig et al. [33] identified phenolic compounds (chlorogenic and ellagic acids, hyperoside, and rutine) and VOCs (above all, eucalyptol) from *E. globulus* leaves recovered from the soil on different days after incorporation. They concluded that the release dynamics of these compounds to the soil environment could be responsible for the observed phytotoxicity.

Various eucalyptus species have demonstrated phytotoxic effects on crops and weeds [94,97–104]. El-Rokiek and Eid [95] observed inhibitory effects from aqueous extracts of *E. citriodora* Hook, applied to the soil, on the growth of wild oats, a resistant weed species very harmful to cereal crops in Europe and Asia. However, most of these works have been carried out under in vitro conditions without considering the soil factor. Approaching the use of plant residues, Zhang and Fu [104] studied the herbicidal potential of the litter biomass of *E. urophylla* S.T. Blake on the establishment of mixed stands with native species, and El-Rokiek et al. [105] corroborated the phytotoxicity of *E. globulus* leaf powder applied as surface mulch. In the west Iberian Peninsula, where eucalyptus plantations occupy large areas, Puig et al. [33,106,107] carried out a sequence of in vitro, greenhouse and field experiments to explore the potential use of *E. globulus* harvest residues (ground foliage and thin branches) incorporated into the soil as a soil amendment for weed control. The results revealed significant inhibitory effects on the germination and early growth of various problematic weed species, such as *A. retroflexus*, *S. nigrum*, *E. crus-galli*, and *D. sanguinalis*, while the maize crop and soil microorganism were unaffected. These phytotoxic effects and an in-depth study on the fate of eucalyptus phenolic and volatile compounds in the soil allowed them to conclude that *E. globulus* biomass was a promising cocktail of allelochemicals for weed control in IWM.

4.10. Eupatorium adenophorum Spreng

Eupatorium adenophorum is a synonym of *A. adenophora* (see Section 4.2). Both synonyms appear interchangeably in the literature; therefore, to preserve the search criteria and respect the scientific nomenclature of the various authors, in this section, we provide the contributions in which the species name *E. adenophorum* is reported.

Different phytotoxic allelochemicals have been identified from its aqueous extracts, e.g., three sesquiterpenes (cadinenes) capable of inhibiting the germination and seedling growth of three target crop species [108]. Two notorious allelochemicals related to the phytotoxicity of *E. adenophorum* are ODA (9-oxo-10, 11-dehydroageraphorone) [109] and Euptox A, the last appraised for its pharmacological properties [110].

The aqueous extract of *E. adenophorum* has been shown to exert in vitro inhibitory effects on the germination and early growth of several weed species [108,111–116]. The aqueous extract acted in *A. thaliana* through several phytotoxic effects on energy metabolism, amino acid dynamics, and phosphate absorption [111]. It is highlighting the observed herbicidal effects of *E. adenophorum* leachates and aqueous extracts on the germination and growth of the weeds *A. retroflexus*, *E. crus-galli*, and *Chenopodium glaucum* L. [114,117]. The extract applied in post-emergence produced yellowing of the leaves of *A. retroflexus* [114]. Li et al. [118], using this plant's aerial parts to produce compost, found an improvement in tomato yield due to increased nitrogen and phosphorus in composted crofton. *Eupatorium adenophorum* residues used as a soil amendment significantly affected the growth and yield attributes of *Amaranthus caudatus* L. and *Vigna unguiculata* (L.) Walp. [115], suggesting that the release of water-soluble allelochemicals could be responsible for this effect.

4.11. Hedera helix L.

Hedera helix is a perennial climbing plant species native to the temperate forests of Europe, which has become invasive in the US Pacific Northwest.

The herbicidal potential of this species has hardly been studied. However, some compounds were associated with phytotoxic effects. The chemical profile is mainly composed of phenolic acids (3,5-caffeoylquinic, gallic, cinnamic, caffeic, neochlorogenic, and chlorogenic acids), flavonoids (rutin, hyperoside, isoquercitrin, quercetin, and kaempferol), triterpene saponins (hederacoside C, hederasaponin B, hederacoside D, and α-hederin), coumarins, and amino acids (proline and alanine) [119].

Some scientists have tested the efficacy of its aqueous extracts. Marian et al. [120] tested the aqueous extracts of *H. helix* and observed strong inhibitions on the germination and seedling growth of *Z. mays* and *P. vulgaris*. Inhibitions in the germination of *Fagus* *sylvatica* L. seedlings by *H. helix* foliar extracts have also been described under water deficit, highlighting the importance of environmental interactions in the phytotoxic process [121]. Phytotoxic effects on *Coreopsis lanceolata* L. seed germination were observed in habitats impacted by *H. helix*, markedly reducing the soil seed bank [122].

Lintz et al. [123] used composted biomass as mulch, obtaining promising results on its use for weed control. Mulching treatments with *H. helix* reduced the cover of *Geranium robertianum* L., another invasive species, by 90% of pre-treatment levels.

4.12. *Lantana camara* L.

Lantana camara is a perennial plant native to tropical America and introduced in many countries as an ornamental plant, becoming one of the 100 worst invasive weeds in the world in more than 60 countries [124].

This species synthesizes several classes of allelochemicals, including phenolic compounds (palmitic, stearic, salicylic, and p-hydroxybenzoic acids, and coumarin), a flavonoid (vitexin), and terpene compounds (α-pinene, germacrene-D, geraniol, eugenol, linalool, and α-cadinol) able to inhibit the growth of different weeds and crops [125–127]. Zheng et al. [128] suggested that the phytotoxic effects of this species were associated with oxidative stress, but there is not enough information to corroborate these results.

The leaf extracts of *L. camara* showed phytotoxic effects on the germination and growth of *A. sativa* [129] and some weeds, such as *Eichhornia crassipes* (Mart.) Solms., *Lemna minor* L., *Lolium multiflorum* Lam., *A. hybridus*, *C. album*, *P. oleracea*, *Conyza canadensis* (L.) Cronq. and *P. judaica* [85,126,130].

In 1984, Achhireddy and Singh [131] observed that the dried residues of roots and shoots of *L. camara* incorporated into the soil caused significant growth inhibitions on the weed *Morrenia odorata* (Hook. & Arn.) Lindl. at a dose of 4 g of dry matter per 100 g of soil, the root tissues being more phytotoxic than the shoots. The phytotoxicity of *L. camara* litter on *R. sativus*, *L. sativa*, *B. pilosa*, *Bidens bipinnata* L. and *Urena lobata* L. has also been evaluated, finding significant inhibitions on the growth of all species and up to 77% on total biomass in the case of *R. sativus* [132]. This experiment also reported changes in soil enzymatic activity since urease, protease, invertase, cellulase, catalase, and soil proteins increased significantly.

4.13. *Leucaena leucocephala (Lam.) de Wit*

Leucaena leucocephala is a tropical leguminous tree species native to Central America that, given its extensive use as fodder and in the timber industry, has expanded and invaded many tropical and subtropical countries [133], becoming a highly invasive and damaging species in non-native habitats. In addition to its high growth and tolerance to poor soils, the invasiveness of this species is associated with allelopathic phenomena. This species presents a great diversity of allelochemicals, among them phenolic acids (p-hydroxybenzoic, protocatechuic, vanillic, gallic, p-hydroxyphenylacetic, and p-hydroxycinnamic acids) and flavonoids (epicatechin, epigallocatechin, gallocatechin, quercetin); however, its phytotoxicity has been mainly associated with the alkaloid mimosine, present in very high concentrations [134,135].

Extracts of the fresh aerial parts and exudates of *L. leucocephala* have shown herbicidal action in laboratory and greenhouse experiments on the germination and growth of multiple target species, such as the crops *L. sativa*, *O. sativa* [134], *Z. mays* [136,137], and *V. unguiculata* [138], and the weeds *B. pilosa* [139,140], *A. hybridus* [139], *Ageratum conyzoides* [141], and *L. multiflorum* [134]. On the other hand, it has been observed that *L. leucocephala* litter used as a soil amendment exerted inhibitory effects on the germination and growth of the crop *V. unguiculata* [138]. Also, besides affecting understory species (*Acacia confuse* Merr., *Alnus formosana* (Burkill) Makino, *Casuarina glauca* Sieber., *Liquidambar formosana* Hance, and *Mimosa pudica* L. [134], reducing the natural biodiversity, *L. leucocephala* causes damage to the crop fields it invades.

Although the abundance of biomass of this invasive species, its use is conditioned by the reported toxicity to different crops, for which relay planting security periods should be assessed and proved.

4.14. *Mikania micrantha* Kunth

Mikania micrantha is an herbaceous vine from the family Asteraceae that rapidly spreads from achenes and stem fragments, taking root quickly and suffocating trees and crops. The species is considered one of the most harmful weed species. Although being native to the tropical regions of America, *M. micrantha* has become an invasive species in Southeast Asia and the Pacific, causing severe damage to tea, teak, rubber, and palm crops [142]. In addition to the effects of competition on other plant species, Ismail & Mah, [143] showed herbicidal effects of *M. micrantha* on nearby plants through leachates and biomass applied to soil as mulch or amendment, inhibiting the growth and germination of the weed species *Asystasia intrusa* Bl., *Chrysopogon aciculatus* (Retz.) Trin. and *Paspalum conjugatum* Berg.

In 2005, a study by Shao et al. [142] elucidated the implication of allelochemicals released by *M. micrantha* in the growth suppression of neighbouring plants. These authors identified four types of phenolic acids from the leaf extracts of *M. micrantha*, and three allelopathic sesquiterpenoids: dihydromikanolide, deoxymikanolide, and 2,3-epoxy-1-hydroxy-4,9-germacradiene-12,8:15,6-diolide, were isolated and characterized for the first time. These compounds were assayed on crops (lettuce, ryegrass, and white clover) and tree species (*Acacia mangium* Willd., *Eucalyptus robusta* Sm., and *Pinus massoniana* Lamb.), inhibiting germination in a dose–response manner. Significant root damage was also observed, affecting plant development and growth. Deoxymikanolide showed the most potent effects on seed germination and root damage. Also, Ma et al. [144] demonstrated, by in vitro bioassays, that VOCs released from the leaves and flowers of *M. micrantha* negatively affected seed germination and seedling growth of *B. pilosa*, *Abutilon theophrasti* Medik., *L. sativa*, and *Chrysanthemum coronarium* L. The volatile terpenoids identified as possibly responsible for the observed effects were α-terpineol, β-ocimene, β-myrcene, α-pinene, and caryophyllene, among others.

Some phytotoxic compounds identified in *M. micrantha* could filter into the soil by rain lixiviate, thus affecting nearby plants' growth and facilitating their position as the dominant species in invaded ecosystems. Also, they could be gradually released during the decomposition of litter or plant residues, making *M. micrantha* eligible for hypothetical use as herbicidal biomass.

4.15. *Parthenium hysterophorus* L.

This annual species of the Asteraceae family, native to the subtropics of America, is one of the most dangerous weeds in the world, as its notorious invasive ability in agriculture fields, especially in Asia and Africa, has caused damage to different crops [145] such as arugula, sunflower [146], sorghum [147], tomato [148], broad beans [149] or maize [150].

Interference and invasiveness of *P. hysterophorus* have been attributed to the sesquiterpene lactone parthenin, present in high concentrations in tissues, together with other identified allelochemicals such as quinic, caffeic, ferulic, vanillic, *p*-anisic, and chlorogenic acids [151]. Notably, increased CO_2 concentration has been shown to promote parthenin production [152], which is relevant in the climate change scenario, pointing out a possible exacerbation of invasiveness. Studies led by Belz et al. [153,154] have discussed the relevance of parthenin in the allelopathic nature of *P. hysterophorus*, because they observed a rapid degradation in soil. Then, Beltz [155] argued that the synergistic interactions among phytochemicals could explain such phytotoxicity.

Different studies reported the herbicidal effects of aqueous extracts on *B. pilosa*, *A. fatua, D. sanguinalis*, *E. indica*, *A. conyzoides*, *Cyperus iria* L., *C. difformis* L., and *Euphorbia hirta* L. [151,156]. Arshad et al. [157] observed that *P. hysterophorus* biomass incorporated into the soil in pot experiments increased plant height and grain and straw yields of rice and subsequent wheat comparable to the green manuring effects of *Trifolium alexandrinum* L. Also, Kishor et al. [158] recorded improvements in the physical, chemical, and biological properties of agricultural soil after the application of *P. hysterophorus* compost in maize crops, increasing cereal yields and reducing weed germination and growth. Such evidence supports the possible use of *P. hysterophorus* biomass for weed control, but always with special care in management to avoid reseeding agricultural fields and surroundings.

4.16. *Pinus* spp.

This coniferous genus is distributed worldwide for its use in forest plantations as fast-growing trees for timber, thus producing vast amounts of residues (needles, thin branches, and bark), which are sometimes redirected to other uses such as the production of essential oils and biomass for energy. Some species of the genus *Pinus* have become invasive in different regions [159].

Different species like *P. halepensis* Miller., *P. densiflora* Siebold & Zucc., and *P. sylvestris* L., have been attributed allelopathic properties due to their significant contents of terpenes (α-pinene, β-cariofilene and α-humulene), phenolic compounds (9α,13β-epidioxyabeit-8(14)en-18-oic acid), and flavonoids (quercetin, catechin, kaempferol, myricetin) [160–163]. Commercial pine extracts have been assayed as bioherbicide, notably reducing the germination rates of several weed species [164].

Nektarios et al. [165] found that *P. halepensis* needels applied to soil showed phytotoxic effects on *A. sativa*, *L. minor*, *F. arundinacea* and *C. dactylon*, reducing root and seedling growth in all of them, being *A. sativa* especially sensitive to the treatment. Fresh *P. halepensis* biomass resulted in more phytotoxic than the senescent one. In other field trials, *P. sylvestris* mulch, consisting of thin branches and needles, efficiently controlled weeds in vineyards and maintained good ground cover throughout the growing season [166]. These experiments strongly indicate the suitability of various pine species for the biomass-based weed control method.

4.17. *Robinia pseudoacacia* L.

Known as false acacia, *R. pseudoacacia* is a leguminous tree species native to North America and widely used in the timber and energy industries, with high biomass yields [167]. The species is also used to reforest and restore soils since it can fix nitrogen, sequester carbon, and tolerate stress. Such characteristics underlie its high invasiveness in new environments, being considered a threat to natural ecosystems.

Evidence of the potential use of the species as a source of allelopathic biomass is scarce. Bektic et al. [168] showed phytotoxic effects of *R. pseudoacacia* and *A. retroflexus* extracts on the germination rate of *Solanum lycopersicum* L. Previously, Nasir et al. [169] explored the implication of allelopathy in the invasive character of *R. pseudoacacia*. They observed that the aqueous extracts of leaves significantly inhibited the root growth of lettuce in a dose–response relationship. Applying leaf biomass mixed with soil at various concentrations in a pot experiment significantly reduced the growth of the roots and hypocotyls of *E. crus-galli*, white clover, lettuce, and Chinese cabbage, the weed species being the most sensitive. Chromatographic analysis of an ethanolic extract of *R. pseudoacacia* leaves led to the isolation of three flavonoids potentially involved in the observed phytotoxicity: robinetin, myricetin, and quercetin. Experimentation still needs to be significantly expanded to appraise *R. pseudoacacia* residues as a tool for weed control.

4.18. *Rottboellia cochinchinensis (Lour.) W.D. Clayton*

Rottboellia cochinchinensis is a self-pollinating allelopathic weed traditionally used as mulch in agricultural fields in Thailand [170]. This weed is native to tropical Asia and has invaded tropical areas in Africa and South America, causing severe damage to fruit orchards and cereal crops like maize, sorghum, and rice.

Although there is little information about the phytotoxic nature of *R. cochinchinensis*, trans-*p*-coumaric acid was isolated and identified as one of the allelochemicals potentially responsible for its phytotoxicity [170,171]. Other two compounds with phytotoxic activity, identified as 9,12-octadecadienoic and 9,12,15-octadecatrienoic acids, were isolated from *L. sativa* roots and shoots exposed to aqueous extracts of *R. cochinchinensis* [172]. There is evidence of inhibitory effects on the germination and growth of weeds in the vicinity of living plants [173], including from assays with *R. cochinchinensis* aqueous extracts [173] and field trials where the density of the weed species *B. pilosa*, *E. crus-galli*, and *A. conyzoides* was significantly decreased after cover cropping or mulching with *R. cochinchinensis* [170,174].

This is an excellent example of how traditional uses of weeds from the local agroecosystems can inspire new tools to be implemented in a holistic IWM strategy.

4.19. *Tropaeolum majus* L.

This species is a perennial herbaceous climbing plant belonging to the Tropaeolaceae family. Native to South America, the species has been introduced in different temperate and subtropical areas of the world as an ornamental plant, becoming invasive in Australia, Spain, and New Zealand [175].

Different allelochemicals from the stems, leaves, flowers, and seeds of *T. majus* have been identified, mainly derived from glucosinolates (glucotropaeloside), organic acids (malic and chlorogenic acids), and flavonoids with reputed phytotoxic activity [176,177]. Among them, glucotropaeloside was shown to produce inhibitory effects on plant development [178,179] by itself or by its degradation product, benzyl isothiocyanate.

The living mulch of *T. majus* grown in the rows of apple trees in an organic orchard [180] was shown to control weed infestation, reducing the germination and size of the annual weed species *Lamium purpureum* L., *Stellaria media* (L.) Vill., *E. crus-galli*, *Galinsoga parviflora* Cav., *Capsella bursa-pastoris* L., and *Poa annua* L., with the rows being mainly covered by perennial weeds such as *Equisetum arvense* L., and *Taraxacum officinale* Weber as a result. This evidence suggests that the residues from *T. majus* removed in local initiatives to fight exotic plant invasions could be applied as allelopathic biomass for weed control.

4.20. *Ulex europaeus* L.

The leguminous shrub *U. europaeus* (gorse) is considered one of the 100 worst invasive species in the world [124]. Its invasive nature is based on rapid growth, N-fixing capacity, resistance to fire, and ease of sprouting, as well as producing many seeds that remain viable for a long time, so it is extremely difficult to eradicate. For these adaptive traits, *U. europaeus* is highly competitive and interferes with the native plants in invaded ecosystems.

Living gorse plants have been shown to produce and emit continuously volatile phytochemicals [181]. The analysis of *U. europaeus* volatile extracts revealed a notable richness of VOCs with a reputed allelopathic nature, including eugenol, isoprene, α-pinene, camphene, sabinene, β-pinene, myrcene, limonene, trans-ocimene, and α-terpinene [30,182]. The species was also confirmed to produce bioactive water-soluble compounds like caffeic, p-coumaric, ellagic acids, and kaempferol, among others [86].

The flowering biomass of *U. europaeus* applied to soil in pot experiments notably impaired the establishment of *A. retroflexus* and reduced the growth of *D. sanguinalis* and *P. oleracea* [37]. Remarkably, Briones-Rizo et al. [183] noticed the inhibitory effects of *U. europaeus* mulch on the emergence of *L. rigidum*, with neutral effects on *L. multiflorum* or *A. sativa*.

The opportunity to increase the effectiveness of weed control through the mixing of the biomass of different species deserves special mention. Similar to the examples described for multispecific cover crops [44], the combination of *U. europaeus* and *C. scoparius* biomass was shown to ameliorate their individual phytotoxicity in vitro [26]. The effect was attributed to synergistic effects among some of their specific VOCs. For instance, eugenol, present only in *U. europaeus*, exacerbated the phytotoxic effects of verbenone, linalool, or terpinene-4-ol, the main phytotoxic terpenoids of *C. scoparius*. Both from in vitro assays of compound mixtures and pot experiments with the application of biomass to soil, Pardo-Muras et al. [26,37] demonstrated the selective phytotoxicity of each shrub species on weeds, as well as the different target physiological processes for the different compounds. Such synergies and multi-MoAs are relevant because the biomass collected may well consist of different allelopathic weed species, which can increase the effectiveness of weed control.

4.21. *Aquatic Weeds*

Aquatic weeds have been poorly studied concerning their potential allelopathic nature, although they are well known to cause imbalances in aquatic ecosystems and significant yield losses in rice, besides invading tanks and pipes for irrigation. Some trials pointed out the phytotoxic effects of several aquatic weeds and yield reductions in rice and other grain crops [184,185].

In 1989, Elakovich [186] conducted an extensive study to evaluate the phytotoxic potential of extracts of 16 aquatic plants: *Brasenia schreberi* J.F. Gmel., *Cabomba caroliniana* Gray, *Ceratophyilum demersum* L., *Eleocharis adcularis* (L.) Roem. & Schult., *Elcocharis obtuse* (Willd.) Schult., *Hydrilla verticillate* (L.f.) Royle, *Juncus repens* Michx, *Limnobiurn spongia* (Bosc) Rich. ex Steud., *Myriophyllum aquaticum* (Vell.) Verdc., *Myriophyllum spicatum* L., *Najas guadalupcnsis* (Spreng.) Magnus, *Nymphaca odorata* Aiton, *Nymphoides cordata* (Elliott) Fernald, *Potamogeton foliosus* Raf., *Sparganium americanum* Nutt., and *Vallisneria americana* Michaux. Extracts were assayed in vitro on *L. sativa* as a model species and the aquatic weed *L. minor*. *Nymphaca odorata* and *B. schreberi* were highly inhibitory and then postulated as candidates for weed management.

More recently, Abbas et al. [187] studied the phytotoxic potential of the extracts and the biomass of five aquatic and marsh species (*Alternanthera philoxeroides* (Mart.) Griseb., *Alternanthera sessilis* R. Br., *Conyza stricta* Willd., *Polygonum barbatum* L. and *E. crus-galli*) on wheat. The aqueous extract of *A. sessilis*, rich in chlorogenic, ferulic, vanillic, and gallic acids, showed the highest inhibition of wheat germination in vitro. For all the assayed species, the allelopathic residues added to soil in field trials significantly affected wheat emergence and growth. Otherwise, Dhole et al. [188] attributed only moderate inhibitory effects to *A. sessilis* extracts on sorghum. Although aquatic species have the potential as allelopathic biomass for weed control, their effectiveness against agricultural weeds and safe management strategies for crops still require profound studies.

4.22. Aromatic Species

Allelopathic phenomena have been reported in many aromatic species, mainly mediated by the emission of VOCs that compose their rich essential oils. Some aromatic species have been postulated as natural herbicides by applying their extracts or essential oils [189]. The feasibility of using aromatic plant tissues as a soil amendment for weed control has been considered by some authors, but their practical implementation, either as cover crops, green manures, or mulch, still requires study. Dhima et al. [190] evaluated the phytotoxic potential of *Foeniculum vulgare* P. Mill, *Pimpinella anisum* L., *Ocimum basilicum* L., *Anethum graveolens* L., *Coriandrum sativum* L., *Petroselinum crispum* (P. Mill.) Nyman ex A.W. Hill, *Phacelia tanacetifolia* Benth., *Mentha* x *verticillata* L., *Origanum vulgare* L., and *Melissa officinalis* L. They conducted lab experiments with plant extracts and field trials with biomass added to soil in maize. Barnyard grass (*E. crus-galli*), common lambsquarters (*C. album*), puncturevine (*Tribulus terrestris* L.), and purslane (*P. oleracea*) suffered inhibition of germination and growth by the extracts and/or biomass of the aromatic species. Many volatile and water-soluble allelopathic compounds potentially involved in the phytotoxicity of these aromatic species were identified by different authors (see Table 1) [191–199]. Previously, Singh et al. [200] showed that mulching with the distillation biomass of *Cymbopogon winterianus* Jowitt ex Bor. (citronella java), a perennial aromatic plant, prevented, on average, 40% yield losses by reducing weed infestation. Batish et al. [201] assessed the herbicidal potential of the aromatic plant *Anisomeles indica* (L.) O. Kuntze (catmint) applied as mulch on wheat crop. The mulch consisting of catmint leaves and roots reduced the emergence and growth of *Phalaris minor* Retz. and other weeds without any adverse effect on the wheat yield. In another work, *Mentha spicata* L. (spearmint) compost was a promising soil amendment since it stimulated tomato growth, increased soil bacterial and fungal abundance, and inhibited weed emergence [202]. Planted as living mulch between rows of apple trees, *Mentha* x *piperita* L. successfully reduced annual weed infestation in an organic orchard [180]. Islam et al. [196] revised the allelopathic properties of a considerable number of species of the family Lamiaceae. Used as biomass incorporated to soil, residues of *Calamintha nepeta* (L.) Savi. inhibited the shoot and root growth of *L. sativa*, *C. album* and *S. alba*, whereas *Salvia officinalis* L. inhibited the shoot length and dry biomass of *Lycopersicon esculentum* Mill. and *Panicum maximum* Jacq.

Table 1. Allelopathic wild plants, weeds, invasive species, and forest residues whose biomass has been assayed as a soil amendment for weed control under pot, greenhouse, or field experiments (see text for specific effects of their plant extracts or essential oils). Weed and crop species for which evidence of phytotoxicity has been reported are included beside the main allelopathic compounds potentially involved in such phytotoxicity. For each column, examples are listed in alphabetical order.

Species Assayed as a Soil Amendment for Weed Control	Family	Susceptible Weed and Crop Species	Allelopathic Compounds Potentially Involved	Refs.
Acacia dealbata	Fabaceae	*Amaranthus retroflexus* *Convolvulus arvensis* *Cyperus* sp. *Portulaca oleracea*	maculosin methyl cinnamate moretenone resorcinol	[48,52,53]
Ageratina adenophora	Asteraceae	*Lolium perenne*	bornyl acetate cadinane p-cymene 4,7-dimethyl-1-(propan-2-ylidene)-1,4,4a,8a-tetrahydronaphthalene-2,6(1H,7H)-dione (DTD) 6-hydroxy-5-isopropyl-3,8-dimethyl-4a,5,6,7,8,8a-hexahydronaphthalene-2(1H)-one (HHO) 6-hydroxykaempferol-7-β-O-glucoside 6-methoxygenkwanin 6-methoxykaempferol 7-methyl ether 3-β-O-glucoside quercetagetin 7-O-glucoside quercetagetin 4′-methyl ether 7-β-O-glucoside	[54–56]
Ailanthus altissima	Simaroubaceae	*Lepidium sativum*	ailanthone caryophyllene oxide chlorogenic acid docosane epicatechin gallic acid galloyl-hexahydroxydiphenoyl (HHDP)-glucose heneicosane hyperoside tetradecanol tricosane rutin	[61–63]

Table 1. *Cont.*

Species Assayed as a Soil Amendment for Weed Control	Family	Susceptible Weed and Crop Species	Allelopathic Compounds Potentially Involved	Refs.
Amaranthus hypochondriacus	Amaranthaceae	*Cynodon dactylon* *Eleusine indica* *Pennisetum clandestinum* *Simsia amplexicaulis*	p-coumaric acid ferulic acid	[70] and the literature cited in
Amaranthus palmeri	Amaranthaceae	*Allium cepa* *Amaranthus palmeri* *Daucus carota* *Sorghum* spp.	chondrillasterol 2,6-dimethoxy-benzoquinone 2-heptanol 2-heptanone 3-methoxy-4-hydroxy-nitrobenzene phytol vanillin	[66] and the literature cited in
Artemisia annua	Asteraceae	*Zea mays*	arteannuin B artemisia ketone artemisinic acid artemisinin camphor eucalyptol α-pinene trans-sabinyl acetate	[74] and the literature cited in
Cassia angustifolia	Fabaceae	*Avena fatua* *Dactyloctenium aegyptium* *Echinochloa colona* *Oryza sativa* *Phalaris minor* *Sorghum bicolor* *Sorghum halepense* *Triticum aestivum* *Zea mays*	sennoside A sennoside B	[75,80]

Table 1. *Cont.*

Species Assayed as a Soil Amendment for Weed Control	Family	Susceptible Weed and Crop Species	Allelopathic Compounds Potentially Involved	Refs.
Cistus ladanifer	Cistaceae	*Cistus salviifolius* *Cytisus multiflorus* *Lavandula stoechas*	apigenin camphene ellagic acid gallic acid kaempferol ledol oxocativol α-pinene quercetin viridiflorol	[81–84]
Cytisus scoparius	Fabaceae	*Amaranthus retroflexus* *Convolvulus arvensis* *Digitaria sanguinalis* *Portulaca oleracea*	caffeic acid p-coumaric acid ferulic acid linalool terpinen-4-ol α-terpineol trans-cinnamic acid verbenone	[30,37,86]
Eucalyptus globulus	Myrtaceae	*Amaranthus retroflexus* *Cynodon dactylon* *Digitaria sanguinalis* *Echinochloa colonum* *Echinochloa crus-galli* *Solanum nigrum*	chlorogenic acid ellagic acid eucalyptol hyperoside rutine	[33,105–107]
Eucalyptus urophylla	Myrtaceae	*Acmena acuminatissima* *Cryptocarya concinna* *Pterospermum lanceifolium*	eucalyptol γ-terpinene	[91,93]
Eupatorium adenophorum	Asteraceae	*Amaranthus caudatus* *Vigna unguiculata*	candinene euptox A 9-oxo-10,11-dehydroageraphorone (ODA)	[108–110,115]

Table 1. *Cont.*

Species Assayed as a Soil Amendment for Weed Control	Family	Susceptible Weed and Crop Species	Allelopathic Compounds Potentially Involved	Refs.
Hedera helix	Araliaceae	*Geranium robertianum*	caffeic acid 3,5-caffeoylquinic acid chlorogenic acid cinnamic acid gallic acid hederacoside C hederacoside D hederasaponin B α-hederin hyperoside isoquercitrin kaempferol neochlorogenic acid quercetin rutin	[119,123]
Lantana camara	Verbenaceae	*Bidens bipinnata* *Bidens pilosa* *Lactuca sativa* *Morrenia odorata* *Raphanus sativus* *Urena lobata*	α-cadinol coumarin eugenol geraniol germacrene D p-hydroxybenzoic acid linalool palmitic acid α-pinene salicylic acid stearic acid vitexin	[125–127,131,132]

Table 1. *Cont.*

Species Assayed as a Soil Amendment for Weed Control	**Family**	**Susceptible Weed and Crop Species**	**Allelopathic Compounds Potentially Involved**	**Refs.**
Leucaena leucocephala	Fabaceae	*Acacia confusa* *Alnus formosana* *Casuarina glauca* *Liquidambar formosana* *Mimosa pudica* *Vigna unguiculata*	epicatechin epigallocatechin gallic acid gallocatechin p-hydroxybenzoic acid p-hydroxycinnamic acid p-hydroxyphenylacetic acid mimosine protocatechuic acid quercetin vanillic acid	[134,135,138]
Mikania micrantha	Asteraceae	*Asystasia intrusa* *Chrysopogon aciculatus* *Paspalum conjugatum*	β-caryophyllene deoxymikanolide dihydromikanolide 2,3-epoxy-1-hydroxy-4,9-germacradiene-12,8:15,6-diolide β-myrcene β-ocimene α-pinene α-terpineol	[142–144]
Parthenium hysterophorus	Asteraceae	weed population in rice fields	p-anisic acid caffeic acid chlorogenic acid ferulic acid parthenin quinic acid vanillic acid	[151,158] and the literature cited in
Pinus halepensis	Pinaceae	*Avena sativa* *Cynodon dactylon* *Festuca arundinacea* *Lemna minor*	β-caryophyllene α-humulene myrcene α-pinene δ-terpinene	[160,161,165]

Table 1. *Cont.*

Species Assayed as a Soil Amendment for Weed Control	Family	Susceptible Weed and Crop Species	Allelopathic Compounds Potentially Involved	Refs.
Pinus sylvestris	Pinaceae	weed population in vineyards	β-caryophyllene α-humulene myrcene α-pinene sabinene	[166]
Robinia pseudoacacia	Fabaceae	*Brassica rapa* *Echinochloa crus-galli* *Lactuca sativa* *Trifolium repens*	myricetin quercetin robinetin	[169]
Rottboellia cochinchinensis	Poaceae	*Ageratum conyzoides* *Bidens pilosa* *Echinochloa crus-galli*	9,12-octadecadienoic acid 9,12,15-octadecatrienoic acid trans-p-coumaric acid	[170–172,174]
Tropaeolum majus	Tropaeolaceae	*Capsella bursa-pastoris* *Echinochloa crus-galli* *Galinsoga parviflora* *Poa annua* *Stellaria media*	chlorogenic acid glucotropaeloside malic acid	[176,177,180]
Ulex europaeus	Fabaceae	*Amaranthus retroflexus* *Digitaria sanguinalis* *Lolium rigidum* *Portulaca oleracea*	caffeic acid camphene p-coumaric acid ellagic acid eugenol isoprene kaempferol limonene myrcene α-pinene β-pinene sabinene α-terpinene trans-ocimene	[30,37,86,182,183]
Alternanthera philoxeroides	Amaranthaceae	*Triticum aestivum*	4-hydroxy-3-methoxybenzoic acid m-coumaric acid p-coumaric acid	[187]

Table 1. *Cont.*

Species Assayed as a Soil Amendment for Weed Control	Family	Susceptible Weed and Crop Species	Allelopathic Compounds Potentially Involved	Refs.
Alternanthera sessilis	Amaranthaceae	*Triticum aestivum*	chlorogenic acid ferulic acid gallic acid vanilic acid	[187]
Conyza stricta	Asteraceae	*Triticum aestivum*	chlorogenic acid ferulic acid m-coumaric acid	[187]
Polygonum barbatum	Polygonaceae	*Triticum aestivum*	m-coumaric acid p-coumaric acid vanilic acid	[187]
Echinochloa crus-galli	Poaceae	*Triticum aestivum*	caffeic acid chlorogenic acid m-coumaric acid p-coumaric acid	[187]
Anethum graveolens	Apiaceae	*Chenopodium album* *Portulaca oleracea* *Tribulus terrestris*	caffeic acid carvone chlorogenic acid germacrene D D-limonene α-phellandrene quercetin rutin	[190–192]
Anisomeles indica	Lamiaceae	*Phalaris minor*	apigenin isoovatodiolide ovatodiolide β-sitosterol stigmasterol	[201] and the literature cited in

Table 1. *Cont.*

Species Assayed as a Soil Amendment for Weed Control	Family	Susceptible Weed and Crop Species	Allelopathic Compounds Potentially Involved	Refs.
Calamintha nepeta	Lamiaceae	*Chenopodium album* *Lactuca sativa* *Sinapis alba*	caffeic acid gallic acid vanillic acid carvone camphor gallic acid isomenthone menthol trans-menthone piperitone pulegone rosmarinic acid	[196] and the literature cited in
Coriandrum sativum	Apiaceae	*Chenopodium album* *Tribulus terrestris*	camphene camphor p-cymene geraniol geranyl acetate limonene linalool linalyl acetate myrcene α-pinene terpinen-4-ol γ-terpinene α-terpineol	[190,193] and the literature cited in
Cymbopogon winterianus	Poaceae	Weed flora dominated by: *Chenopodium album* *Cynodon dactylon* *Digitaria sanguinalis* *Gnaphalium indicum*	citronellal citronellol geraniol	[200]

Table 1. *Cont.*

Species Assayed as a Soil Amendment for Weed Control	Family	Susceptible Weed and Crop Species	Allelopathic Compounds Potentially Involved	Refs.
Foeniculum vulgare	Apiaceae	*Chenopodium album* *Portulaca oleracea* *Tribulus terrestris*	apigenin apigenin-7-O-glucoside caffeic acid 4-O-caffeoylquinic acid cirsiliol chlorogenic acid p-coumaric acid epicatechin naringenin protocatechulic acid quercetin quinic acid rutin salviolinic acid syringic acid trans-ferulic acid	[190,194]
Melissa officinalis	Lamiaceae	*Echinochloa crus-galli*	α-cadinol camphene β-caryophyllene citronellal β-citronellol α-elemol geraniol germacrene D limonene linalool α-pinene β -pinene	[190,195]

Table 1. *Cont.*

Species Assayed as a Soil Amendment for Weed Control	Family	Susceptible Weed and Crop Species	Allelopathic Compounds Potentially Involved	Refs.
Mentha piperita	Lamiaceae	Weed flora dominated by *Hypochaeris radicata*	cis-ocimene p-cymene eucalyptol limonene β-myrcene α-pinene β-pinene sabinene trans-ocimene	[180] and the literature cited in
Mentha spicata	Lamiaceae	Weed flora dominated by: *Amaranthus retroflexus* *Chenopodium album* *Cynodon dactylon* *Datura stramonium* *Portulaca oleracea* *Sorghum halepense*	β-bourbonene carvone β-caryophyllene eucalyptol limonene pulegone trans-piperitone oxide	[202] and the literature cited in
Mentha x *verticillata*	Lamiaceae	*Chenopodium album* *Tribulus terrestris*		[190]
Ocimum basilicum	Lamiaceae	*Chenopodium album* *Echinochloa crus-galli* *Tribulus terrestris*	chloramben-methyl elaidic acid methyl ester linoleic acid methyl ester methyl linolelaidate 9,12-octadecadienoic acid squalene 2,5,5-trimethyl-2-cyclopentenone	[190,196] and the literature cited in
Origanum vulgare	Lamiaceae	*Chenopodium album* *Echinochloa crus-galli*	apioline α-cadinol carvacrol β-caryophyllene caryophyllene oxide methyleugenol myristicin γ-terpinene thymol	[190,196] and the literature cited in

Table 1. *Cont.*

Species Assayed as a Soil Amendment for Weed Control	Family	Susceptible Weed and Crop Species	Allelopathic Compounds Potentially Involved	Refs.
Petroselinum crispum	Apiaceae	*Chenopodium album*	oxypeucedanin oxypeucedanin hydrate pabulenol N-(2′-phenylethyl)-hexanamide	[190,197]
Phacelia tanacetifolia	Boraginaceae	*Chenopodium album* *Echinochloa crus-galli* *Tribulus terrestris*	chlorogenic derivative ellagitannin eriodictyol p-hydroxybenzoic acid luteolin derivative	[190,198]
Pimpinella anisum	Apiaceae	*Chenopodium album* *Echinochloa crus-galli* *Tribulus terrestris*	estragole eugenyl acetate α-humulene β-humulene limonene linalool trans-anethole	[190,199]
Salvia officinalis	Lamiaceae	*Lycopersicon esculentum* *Panicum maximum*	camphor β-caryophyllene eucalyptol α-humulene trans-thujone viridiflorol	[196] and the literature cited in

Aromatic plants are usually grown in agroecosystems for their ecosystem services, such as pollinator attraction, physical barriers, and plague deterrents, besides culinary and medicinal uses. They are grown worldwide as cash crops devoted to essential oil distillation for the pharmacological, cleaning, cosmetic, and perfume industries. Therefore, considering their general knowledge, regular use, abundance, and reported phytotoxicity, aromatic plants—and even their industrial residues and byproducts—are promising candidates for use as allelopathic biomass for weed control.

5. Benefits and Services Provided by Adopting Plant-Based Approaches in Integrated Weed Management

This review has revisited the benefits of plant-based weed management approaches [10], both green manuring with allelopathic cover crops and the less explored biomass from allelopathic agroforestry and invasive species. From a holistic point of view, the proposed use of biomass as a soil amendment for weed control complies in different ways with the DNSH (Do No Significant Harm) principle and can contribute to achieving the extra environmental objectives of ecological transition (Regulation (EU) 2020/852 of the European Parliament and of the Council of 18 June 2020). Such a contribution is justified as follows:

(i) In *protecting water resources*, the alternative use of solid slow-release plant-based herbicides instead of emulsifiable synthetic herbicide formulations can mitigate agricultural runoff and spills to fresh water and the sea. The bioactive principles present at very low individual concentrations in allelopathic cover crops and biomass (VOCs and water-soluble allelochemicals) are secondary plant products and metabolites that are innocuous for wildlife once diluted in fresh waters and the seas, so the side effect of the off-target movement of synthetic herbicides is eliminated [10].

(ii) Under a *circular economy* perspective, the residues and surplus allelopathic biomass derived from various activities in the agroforestry sector could be redirected to complementary agricultural use.

(iii) In *preventing pollution*, the use of allelopathic biomass and potential new biomass-based products for weed control satisfies the demands of society and legislation for new products and methods for weed control that are more effective, economical, healthy, and respectful of the environment. The bioactive principles of plant-based herbicides are secondary plant metabolites that, at the effective herbicide doses, are generally innocuous or even beneficial for human health: they have been widely used, and their safety has been tested, to the bioactive concentrations of each compound in the allelopathic biomass, or are authorized for use in human medicine, veterinary medicine, cosmetics, and the food industry. Many (essential oils, phenolic acids, or flavonoids) are currently considered true nutraceuticals.

The effectiveness of green manuring with allelopathic cover crops or allelopathic biomass is based on powerful intra- and interspecific synergies (e.g., [28]) that occur among the natural bioactive principles of different chemical classes contained in the tissues of the allelopathic species. Acting together as a natural cocktail, they are capable of inhibiting the germination and early growth of many weed species. Moreover, such effectiveness relies upon the phytotoxic interactions of different allelochemical substances that occur at pretty low individual concentrations (in the order of hundredths of ppm of each volatile compound released into the soil pores and in units to hundredths of μmol/L of each phenolic compound in the soil water (e.g., [28,33]), which are slowly and gradually released from the biomass once applied to the soil [33]. These maximum quantities that can be released into the agroecosystem by the plant-based herbicides over weeks to months have been measured to be well below the phytotoxicity threshold of each active ingredient separately [26,28,33]. These practices can reduce the unwanted effects of synthetic herbicides whose effective doses of one or few active ingredients are much higher and are released at their maximum concentration from the moment of their application.

In reducing invasion by opportunistic weeds, allelopathic cover crops and biomass do not provide one but multiple modes of action on the germination and early growth of many weeds, as many as different molecular targets have the specific composition of allelochemicals. Contrary to the available synthetic herbicides having one or a few active ingredients, these facts make the appearance of highly competitive resistant genotypes of weeds very unlikely.

(iv) Concerning the *protection and recovery of biodiversity in agroecosystems*, the use of allelopathic green manures from cover cropping or biomass available from the agroforestry follows the principles of pest control in organic agriculture, good agricultural practices, and the holistic trends in IWM. These practices do not eradicate weeds but instead maintain their populations at stable levels that are not competitive with the crop, gradually reducing the soil seed bank. In this way, the desirable ecosystem services [203] provided by weeds—redefined by Merfield [204] as *aliae plantae*, the "other plants"—would be preserved (for instance, soil cover and aeration, protection against erosion, organic matter, the attraction of pollinators, crop protection against diseases and pests, food or shelter from auxiliary meso-, and macrofauna). So, the agroecosystem's diversity of 'partner' species and functional types that guarantee its stability, resilience, and that sustainable production would be maintained.

Also related to the *protection of agroecosystem biodiversity*, most of the allelopathic plant species compiled in this review are abundant, highly productive, and not protected or vulnerable. Others, such as aromatic species, could even be produced for the purpose of this use. Also, the explained characteristics of multi-MoAs provide allelopathic plant-based approaches with low susceptibility to generating highly competitive resistant biotypes.

(v) In *mitigating climate change*, reusing agroforestry residues and weeds decreases the emission of GEIs after the usual burning. Moreover, adopting plant-based methods in IWM can reduce the fuel consumed for mechanical weeding. In a post-herbicide era, *sensu* Marshall [205], applying allelopathic biomass and cover crops for weed control would decrease the consumption of the available synthetic herbicides and, consequently, the carbon footprint derived from their production processes.

On the other hand, incorporating cover crops or plant residues from agroforestry and invasive weeds into agricultural soils (the last otherwise being discarded or incinerated) provides organic matter and metabolizable products that stimulate microbial activity and improve soil physic-chemical properties [32–37,107], with a contribution to carbon sequestration. Concomitantly, these plant-based agricultural methods can increase the soil's water retention capacity by conferring porosity and preventing excessive evaporation, potentially contributing to water use efficiency in a water scarcity scenario.

(vi) In the *adaptation to global change*, it is known that global warming and drought can reduce the efficacy of available synthetic herbicides and promote the appearance of resistant weed ecotypes. On the other hand, warming, drought, and globalization are expected to enhance the proliferation of highly competitive weeds outside their native ranges. These recently appearing problems can compromise present and future agricultural production, which requires new efficient tools and methods for weed control. The biomass from allelopathic agroforestry and invasive plant species as soil amendments for weed control has unique characteristics that could meet such demands.

6. Concluding Remarks

The specific plan-based approach covered in this review is relevant in a contemporary IWM where cover crops are called to be fundamental tools [10]. Allelopathic cover crops and allelopathic biomass available from agroecosystems worldwide combine the characteristics of biological weed control but also of chemical weed control, thus providing a hybrid "little hammer" for IWM [205,206]. From the studies reviewed herein, in contrast to herbicide-based control, allelopathic plant-based approaches involve powerful synergies among many bioactive principles of different chemical classes contained in the tissues of the allelopathic species. Each of these allelochemicals' natural concentrations is extremely low, and they are slowly and gradually released by lixiviation, volatilization, or exudation from the roots of living allelopathic cover crops or from the plant residues once applied to the soil (Figure 1). Moreover, the natural cocktail of allelochemicals provides multiple MoAs, which probably would reduce the appearance of resistant weeds. Still, plant-based weed management can maintain the functional diversity of the "other plants" and so their wide variety of ecosystem services [203,204], thus building a scenario far from "bare grounds and often reinfestations that must be treated again (and again)" in the synthetic herbicide-based strategy [10].

It is worth emphasising that, similar to the careful selection and use of cover crops to avoid becoming a weed [10], the management of allelopathic biomass must also avoid the accidental spread of propagules, being used in the early flowering stage both to achieve its highest control potential and to prevent seed dispersal. Some post-harvest treatments [46] should be required to eradicate the vegetative propagules of invasive weeds before application to the agricultural soil.

Finally, using the available allelopathic biomass from agroforestry as soil amendments for weed control would offer extra opportunities for the science and practice in a holistic IWM. On the one hand, the investment of resources and time into producing cover crops would be alleviated; on the other hand, a new use of some agroforestry residues and a sink for harmful weed biomass would be provided as a part of a circular local economy.

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