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Integration of Allelopathy for Sustainable Weed Management in Agriculture: A Review

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ABSTRACT

Inhibiting plant growth and development, weeds cause crop failure, causing a significant threat to agricultural output. Compared with any other pest, weeds reduce agricultural yields. Consequently, synthetic herbicides have become widely used for weed control. However, the widespread use of synthetic herbicides affects ecosystems and human health. The numerous adverse effects of synthetic herbicides have prompted scientists to seek less harmful alternatives. It is possible to significantly decrease the use of pesticides by implementing the method, i.e., allelopathy. In writing this review, we aimed to help readers better understand many allelopathic species that produce useful allelochemicals for both organic and conventional farming. The main goal of this research topic is SDG 2: Zero Hunger. The objectives of this SDG are to improve nutrition, achieve food security, eradicate hunger, and advance sustainable agriculture. The study also helps to understand the dynamics of terrestrial ecosystems and the relationships between plant species, which are crucial for sustainable land management and agricultural productivity. It is secondary to SDG 15 (Life on Land). Allelopathy is becoming increasingly significant in sustainable agriculture despite these obstacles, providing a way to cut chemical inputs while still controlling weeds effectively. We expect that more studies will be conducted into allelopathy as a weed management strategy for a complete, long-term, and ecologically acceptable weed control plan.

Keywords: Allelopathy; Weed management strategy; Bioherbicide; Allelochemical; Synthetic herbicide

1. INTRODUCTION

1.1. Allelopathy

When one plant releases chemicals into the environment that can affect another plant, either positively or negatively, this phenomenon is called "allelopathy"[1]. Such biochemicals are referred to as "allelochemical." Allelochemicals are released from plant components by leaching, volatilisation, residual decomposition, and root exudation. Allelochemicals can either hinder or encourage the growth of both shoots and roots. The allelochemicals, which include phenolic compounds, shorten the root and shoot lengths. These allelochemicals may impede growth by interfering with typical plant activities. Released allelochemicals can compromise a plant's nutrient source if they attack a naturally occurring symbiotic connection, hinder the plant's capacity to absorb soil nutrients, or both. Allelopathy in the biological system is depicted in Fig. 1. According to the illustration, the above-ground interactions are moderated by volatile organic compounds. On the other hand, the rhizosphere's below-ground interactions are facilitated by phytotoxins and root exudates generated during the breakdown and leaching of litter. Because microorganisms change the allelochemicals into new forms, they can alter, enhance, or lessen the allelopathic effects.

1.2 Allelochemicals

To protect themselves from diseases, herbivores, and even other plants, plants produce allelochemicals[2]. Allelopathy in chemical ecology studies the effects of microbes and plant materials on the growth and development of different plants. This may impact the growth of nearby plants in a favorable or wrong way. Allelon is defined as "of each other or mutual," and pathos is defined as "to suffer or feel." These two Greek terms are the source of allelopathy. While Austrian physicist Hans Molisch may have coined the word "allelopathy" in 1937, understanding plant interactions' chemistry goes back thousands of years. In the first century A.D., the Roman scholar Pliny noted that walnut trees (*Juglans* spp.) suffered damage from chickpeas, and the Greek botanist Theophrastus said the same thing around 300 B.C. Agricultural and natural processes such as root exudation, leaf volatilisation, residue decomposition, and leaf and litter leaching release allelochemicals from plant components. Due to their impacts on the microbiome,

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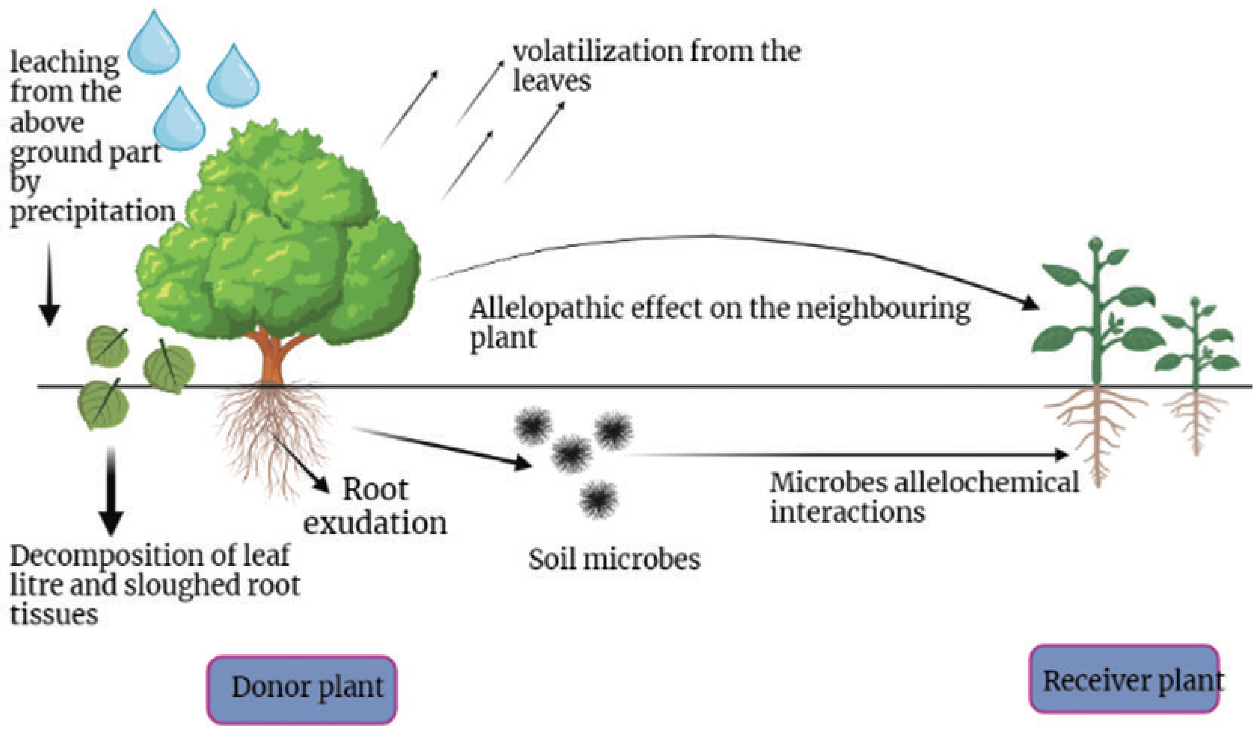

Figure 1. Representing the allelopathic effect on a neighboring plant.

allelochemicals have the potential to alter rhizosphere soil properties or hinder the germination, growth, and establishment of nearby plants[3].

Allelopathic chemicals have the potential to be utilised as natural biodegradable pesticides due to their essential role in managing plant communities. Advancements in separation and structural elucidation methods have led to the recent discovery, isolation, and characterisation of active chemicals[4]. Allelochemicals are secondary metabolites that plants and microorganisms similarly produce. The allelochemicals of rice have been categorised into fourteen categories based on their molecular similarities[5].

Some examples of allelochemicals are ethylene, salicylic acid, and gibberellic acid, all used as plant growth regulators. The efficacy, bioavailability, and action mechanisms of allelochemicals[6] are unknown. The function of several recently discovered allelochemicals in plants remains unknown. Also, several allelochemicals have limited or evaded attempts to determine their specificity and effectiveness[7]. As an alternative to chemical herbicides, they work well. Numerous plant species have been categorised globally due to their allelopathic effects; further research is needed on these impacts.

1.3 Weed

Generally, people consider any plant that grows in an unwelcome spot a weed. Weeds are species that disrupt agricultural methods, negatively impact ecosystem structure and function, or are widely distributed. Due to multiple factors, weeds must be removed from the environment. These issues include their ability to contaminate crops, poison cattle, restrict the variety of pastures available to cattle, and reduce agricultural output.

Weeds in agricultural systems cause many financial problems. Farm profitability decreases directly from weed infestations, which reduce crop and pasture production. No one farm is immune to the financial toll that weeds take. An entire sector may have widespread repercussions if weeds alter the supply or demand for an item. A phenomenon called "externalities" can occur when weed populations on one farm are left uncontrolled and end up in adjoining areas[8].

Weeds significantly threaten agricultural and natural vegetation systems in Australia. The naturalised flora of Australia includes roughly 2700 species that are considered non-native. Seven hundred ninety-eight are recognised as a big issue in natural ecosystems. One thousand two hundred sixty-six species are a problem for farming, with 35 % being extremely problematic. There are now sixteen of these species that have nationwide or state-wide coordinated eradication campaigns due to their perceived influence on agricultural ecosystems.

A weed is any unwelcome plant that interferes with or threatens human health or way of life. In a crop production system, weeds impair output because they take space, water, nutrients, and sunlight away from the crops. As a result of weed management, agricultural output is negatively affected, and crop production costs are increased. How much output is lost because of weeds depends on the density of weeds, when they emerge, what kinds of weeds they are, and the kind of crop it is[9]. It is estimated that weeds account for as much as 40 % of worldwide crop loss. Weeds are responsible for almost $8 billion of crop loss in the US annually. U.S. corn and soybean yields are most negatively affected by weeds. U.S. soybean yield fell by 50 %, and Canadian maize yield fell by 50 % due to weed interference between 2007 and 2013[10]. According to estimates, weeds in grain harvests cost Australia and India 2.52 billion USD and 11 billion USD annually in lost output, respectively. Every year, weeds cause China to lose about 3 million metric tonnes of grain. The findings show that weeds pose a major risk to crop production and cause significant economic losses on a global scale[11].

2. MATERIALS AND METHODS

Different searching strategies were used in this review to search for papers used for analysis. Plant science and agronomy electronic journal databases were used to retrieve published articles. The focus was on Google Scholar, the Web of Science, and Science Direct. Specifically, the researcher focused on experimental studies that examined the effects of different weed extracts on weeds and cultivated crops between 2013 and 2022. An iterative search using the combination of the following search terms was conducted: "allelopathic potential of weeds," "inhibitory effects of weeds," and "weed management techniques. This review found 162 peer-reviewed original studies, of which only 26 were analysed and evaluated.

3. RESULTS AND DISCUSSION

3.1 Weed-Controlling Plants with Allelopathic Potential

3.1.1 Eucalyptus (Eucalyptus spp.)

Numerous investigations have looked into the allelopathic effects of different *Eucalyptus* species; containing allelochemicals in their leaves, bark, and roots, including volatile terpenes and phenolic acids. This species' leaves are rich in several oils and resins that can directly or indirectly affect the growth of nearby plants, seeds, and bacteria[12]. This plant includes volatile terpenes with allelochemical properties, including pinene, limonene, and 1, 8-cineol. In greenhouse research, Babu and Kandasamy (1997) found that leachates from fresh bluegum eucalyptus leaves reduced resprouting of *Cyperus rotundus* by (57–68) % and *Cynodon dactylon* by (82–89) %. The petri dish experiment demonstrated that 1,8-cineol, a well-known allelopathic chemical found in eucalyptus leaves, could decrease bermudagrass growth by 66 % at a 25 % (v/v) concentration. Additionally, it reduced the germination of common purslane by 90 % and common *Amaranthus retroflexus* by 80 %. It has been demonstrated that 1,8-cineol affects germination, root growth, and mitosis[13].

3.1.2 Fine Fescue Grasses (Festuca Rubra, Festuca Arundinacea)

These are known to evict nearby species due to the allelochemicals they release into the land via their roots. Numerous studies have investigated whether fine fescue grasses can effectively suppress weed growth using their poisonous root leachates[14]. In both greenhouse and field studies, the germination of birdsfoot trefoil was reduced by aqueous extracts of dried tall *F. arundinacea* shoots and roots. Weston (1990) showed that *F. rubra*, whether set down as live mulch or dead sod, worked remarkably well in controlling weeds in a no-tillage field trial. The compound M-tyrosine inhibited the growth of common dandelion, white clover, and enormous crabgrass. The natural herbicide m-tyrosine stunts following germination. Several plant species have demonstrated that it influences cell development and division.

3.1.3 Rice (Oryza Sativa L.)

Many studies have examined rice's allelopathic potential. Various rice varieties are allelopathic, according to studies conducted in the field and the lab. For their allelopathic effects on *Heteranthera limosa*, researchers examined 5,000 different types of rice; 191 of these variations showed detectable impacts. As for *Monochorea*, or barnyard grass, another study indicated that 45 different kinds of rice had allelopathic activity. In 2004, Lee et al. studied 749 rice varieties and found that japonica rice cultivars successfully prevented barnyard grass, the most common allelopathic weed, from growing roots. Rice extract includes phytotoxic chemicals, including terpenoids, phenolic acids, phenyl alkanoic acid, indoles, benzoxazinoids, and fatty acids[15]. Tricin and momilactone B are the allelochemicals in rice varieties with allelopathic properties. Rice leftovers contain an array of autotoxins, including phenolic acids. As Xuan *et al.* (2005) pointed out, these chemicals do double duty: they boost rice output and prevent paddy weeds from growing. To help with weed control, you can directly apply rice hull, rice flour, and rice straw. The more we learn about the mechanisms of action of allelopathic rice cultivars, the more the possibility of using this method for weed control grows.

3.1.4 Shorghum (Sorghum Bicolor (L.) Moench)

To suppress weeds, sorghum uses a combination of hydrophobic components, such as sorgoleone, and hydrophilic molecules, such as phenolic acids and aldehyde derivatives of these acids. Sorgoleone was extracted in 1986 by Netzly and Butler from the sorghum root exudates. As much as 90 % of the chemicals found in sorghum root exudates are sorgoleone-related. According to Yang *et al.* (2004), Corleone is derived from sorghum root hair cells. Given its effectiveness against various weeds, sorgoleone has been classified as a powerful bioherbicide. Evidence suggests it is more active than other allelochemicals, including juglone, phenolics, and terpenoids[16]. Using sorghum can improve weed control techniques, including surface mulching, soil mixing, spraying, and intercropping. Studies have demonstrated that sorghum's multiple parts can significantly decrease soil weed biomass, sometimes by 25 % to 50 %. By applying sorgaab, a foliar treatment of sorghum water extract, to maize plants, yields were up 44 %, while purple nutsedge density and dry weight were down 67 %.

3.2 Allelopathic Plants having Strong Allelochemical Properties against Sensitive Plants

Scientists investigated some plants with allelochemical solid properties, which harm the target plants Table 1.

3.3 Allelopathic Effect of Some Exotic Invasive Plants

The invasive plant species *Lantana camara* has its roots in the Americas and is a significant problem for ecosystems and forest resources since it takes over pastures, woods, tea plantations, and even orchards. Its toxicity makes it a harmful weed. Animals and humans alike risk poisoning if they carelessly consume it. The severe allelopathy of *Lantana camara* can inhibit the growth of neighboring plants, as recently discovered[26].

Ageratum conyzoides L. is one of the most troublesome weeds in southern China. A recent study demonstrated that the allelopathy is caused by phenolic compounds extracted from the remaining leaves[27].

The leaves of *Parthenium hysterophorus* L., the ragweed plant, contain the highest concentration of parthenin, a sesquiterpene lactone derived from pseudoguanolides. Parthenin is present throughout the plant. *Amaranthus viridis*, *Cassia occidentalis*, *Bromus tectorum*, and *Phalaris minor* all had decreased height and dry weight following pre- and post-emergent Parthenon treatment.

Allelochemicals can be found in every part of common Lantana (*Lantana camara*). The plant has a wide variety of allelochemicals[28]. The two most potent allelochemicals in common *Lantana* are lantadene A and B.

Researchers examined how *Amaranthus viridis* affected agricultural production and seed germination in controlled and wild settings[29]. Vegetable seed germination was significantly decreased when extracts from the *Amaranthus* plant's roots, flowers, stem, and leaves were added. Allelopathic effects were evident in the tomato seedlings in the pot experiment since two treatments resulted in slower development rates. Unfortunately, the results of the field studies did not show any significant effects. The electrical conductivity of all *Amaranthus* preparations was found to be exceptionally high. Seeds exhibited either no germination or very little germination at concentrations beyond 3.12 mg ml-1 and an electrical conductivity (E.C.) value of 2.1 ms cm-1, indicating that the E.C. values of the diluted extracts were lower in the dilution experiment. The increased E.C. values associated with the allelopathic effect could be due to plant allelochemicals, although none were found in this study. To learn where the allelopathic impact comes from and how long it lasts, as well as the dangers it presents to crops, more harm must be done.

It was discovered that extracts of *Amaranthus viridis* caused allelopathic effects on ryegrass in petri dish bioassays. Dried material extracts significantly reduced germination percentage and root and shoot growth compared to the control group. Extracts from freshly harvested plants were more effective at 50 % and 100 % concentrations on ryegrass. The next step was to use a mixture of half-dried and half-fresh plant extract to remove ryegrass altogether. The results also suggest that the phytotoxicity of *Amaranthus viridis* is affected by different extraction procedures.

Applying *Lantana camara* leaf extract to *Lactuca sativa* impeded germination and cellular development and boosted oxygen creation[30]. In a similar vein, *L. camara* leaf extract stifles the germination and growth of *Eichhornia crassipes*, *Vigna unguiculata*, *Capsicum pubescens*, *Vigna radiata*, and *Funaria hygrometrica*.

Table 1. List of plants that are allelopathic and have potent allelochemical effects on delicate plants

Allelopathic plant	Main allelochemical present	Target species	References
Parthenium hysterophorus L.	Parthenon	Amaranthus (*Amaranthus viridis* L.)	17
Lantana camara L.	Lantadene A and B	Common oat (*Avena sativa* L.)	18
Piper longum L.	Sarmentine	Wild mustard (*Sinapis arvensis* L.)	19
Sunflower (*Helianthus annuus*)	Heliannuols	Tumbleweed (*Amaranthus album* L.)	20
Azadirachta indica A. Juss.	Nimbolide B	Lettuce (*Lactuca sativa* L.)	21
Digitaria sanguinalis (L.) Scop.	Veratic acid	Wheat (*Triticum aestivum* L.)	3
Juglans nigra L.	Juglone	Horseweed (*Conyza canadensis* (L.))	22
Eucalyptus spp.	1,8 - cineol	*Amaranthus* (*Amaranthus retroflexus* L.)	23
Festuca spp.	M-tyrosine	Large crabgrass (*Digitaria sanguinalis* (L.))	24
Oryza sativa L.	Tricin	Jungle rice (*Echinochloa colona* (L.))	25
Sorghum bicolor (L.) Moench	Sorgoleone	Common amaranthus (*Amaranthus retroflexus* L.)	16

L. camara extracts include chemical components with antibacterial and fungicidal activity, and these effects have been experimentally confirmed; and also used to treat infectious diseases in its traditional medicine form. Essential oil has a Minimum Inhibitory Concentration (MIC) of 1000 ppm against *Proteus mirabilis* and *Bacillus subtilis*, as per Sonibare and Effiong[31]. At a Minimum Inhibitory Concentration (MIC) of 10,000 ppm, it is efficacious against *Pseudomonas aeruginosa*, *Candida albicans*, *Salmonella typhi*, and *Staphylococcus aureus*. Antimicrobial activity of an extract of *Lantana camara* flowers, leaves, stems, and roots against *Escherichia coli*, *Pseudomonas aeruginosa*, *Staphylococcus aureus*, and *Staphylococcus saprophyticus*[32]. *Lantana camara* flower extract has potent antimicrobial activity. Different shades of yellow, purple, red, and white are available. Flowers from the *Lantana camara* plant had similar antimicrobial effects. Petroleum ether root extract showed weaker antibacterial efficacy against *Pseudomonas aeruginosa* and *Staphylococcus saprophyticus*. The chloroform extract inhibits *Staphylococcus aureus* growth over a moderate area (5m). A chloroform stem extract slowed the development of *Staphylococcus saprophyticus*[33].

Other weed species also have their distinct allelochemicals. These allelochemicals can serve as models for designing new herbicides, some of which may employ unique modes of action.

3.4 Allelopathic Techniques Used in Weed Control

Incorporating allelopathic crops into rotational sequences, planting them next to cash crops, using them as intercrops, using them as living or dead mulches, working crop residues into the soil, and using their allelochemicals as bioherbicides are all effective ways to control weeds in agroecosystems[34]. Due to the unique context of climatic conditions, different species, agricultural practices employed, and financial constraints, allelopathy is a very flexible weed management method. Although allelopathy can be utilised in a wide range of cropping systems, its most significant utility lies in the difficult task of weed management in organic farming and other low-input, low-till agricultural practices. As a bonus, the allelopathic weed control methods can be employed independently to maximize effectiveness.

3.4.1 Crop Rotation

Planting various crops in the same area is one example of a traditional farming strategy. This method has many uses and benefits. Soil microorganisms, organic matter, fertility, and crop yields can all be improved. The most effective way to minimize weed establishment and diminish the soil seed bank is crop rotation. These methods prevent the growth of invasive and specialised weeds while allowing a diverse weed community with low concentrations of individual weed species to flourish[19]. This approach does not entirely eradicate stubborn weeds but makes future direct management strategies more effective by reducing their ability to grow. An allelopathic crop can release allelochemicals into the soil through root exudation, decomposition of plant wastes, and leaching from plant foliage, reducing weeds in the present and subsequent crops. Once released into the rhizosphere, Allelochemicals can hinder seed germination directly or undergo indirect transformation by microbes into more active, less active, or inert substances.

3.4.2 Cover Cropping

"Cover cropping" is a harvest-boosting technique that involves growing herbaceous plants in monoculture or intercropping for a season or year[16]. Protecting soil from erosion, reducing nutrient leaching (particularly nitrates), increasing soil organic matter and microbial activity, improving soil hydraulic properties and structure, conserving soil moisture, managing weeds and pests, and many more ecosystem services are provided by cover crops[26]. These advantages lead to better harvests in the future. While they may sound different, "cover cropping," "mulching," "intercropping," and "green manuring" all refer to the same thing[29]. Incorporating plant leftovers into the soil when intercropping with a cash crop makes cover crops worthwhile, such as green manures and dead or live mulches.

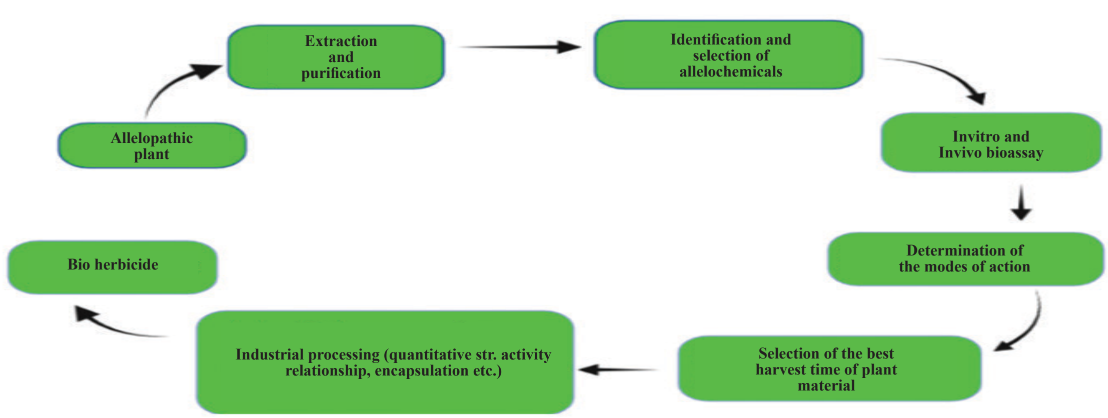

Figure 2. Steps for producing a commercial bioherbicide.

3.4.3 Bioherbicides

Researchers have created bioherbicides derived from live species or their secondary metabolites to manage weed populations without harming non-target creatures[35] Fig 2. This investigation will exclusively focus on allelochemicals derived from plants. Due to their many benefits, plant-based allelochemical bioherbicides are becoming more popular to reduce reliance on synthetic herbicides, eradicate weed resistance, and lessen their adverse environmental effects. These features include strong soil biodegradability, chemical stability, and water solubility.

4. FUTURE PROSPECTIVES

We have already established that weed control with a few allelopathic species has much potential. Much more work is required to discover new allelochemicals and improve upon existing ones, but there has been some success in studying allelopathy. Notwithstanding the many challenges, the potential benefits of researching allelopathy as a novel weed management strategy outweigh the drawbacks. It is too early to tell whether using extracted allelochemicals on different crops is safe. It would be beneficial to conduct more studies on the mechanisms of allelochemical selectivity, their modes of action, interactions with other species, and application techniques. Another novel application of transgenic allelopathy is in agricultural output.

5. CONCLUSION

This review focused on various allelopathic species that produce useful allelochemicals that can be used in conventional and organic farming. Using allelopathy in organic weed control can lessen the need for synthetic herbicides. Allelopathic crops have the potential to enhance the efficacy of more conventional weed management strategies, such as mulching, crop rotation, cover crops, and intercropping. Plant extracts with allelopathic characteristics and lower chemical doses may be used in sustainable weed management strategies. Since only a tiny number of crop-selective natural herbicides derived from allelochemicals are currently on the market, there is an immediate need to increase production. Weed control will benefit from the increased discovery, testing, and application of allelochemicals made possible by modern biotechnological techniques and improved extraction procedures. Although it is becoming more and more challenging to eliminate the need for chemical weed control, an integrated weed management strategy could prove helpful. Herbicide resistance can be avoided, production costs can be decreased, weed control can be improved, and herbicide use can be decreased by combining allelochemicals or by-products of allelopathic species with other weed management techniques.

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