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Modern techniques, avenues for integrated weed management

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Abstract
Current awareness of the impact on the environment through intensive agriculture. It is primarily pesticides and herbicides that are known to have driven the research community and government institutions Programming and development of new environmental-friendly agronomic practices for weed control. This has resulted in integrated weed management and IPM becoming mandatory. Weeds are generally considered to be the most important biotic factor affecting crop production especially in organic farming. This review aims to satisfy that need by outlining the fundamentals of integrated weed management (IWM)/non-chemical weed control and its application to the development of optimal strategies for herbaceous field crops such as ecological weed control, mechanical weeding, mulching, intercropping, cover crops, grow allelopathic crop and bioherbicide. Integrated weed management, inclusive of application of bio-herbicides, is an emerging strategy for weed control toward sustainable agriculture. Generally, bio-herbicides are either obtained from plants containing phytotoxic allelochemicals or some disease-carrying microbes which can suppress weed populations. Although bio-herbicides showed immense potential to deter weed seed germination and growth, only a few *in vitro* studies have been carried out on the physiological responses they elicit in weeds. Number of commercial bioherbicide products available currently, the impact of bioherbicides on weed physiology, and factors that may influence their efficacy.

Keywords: Integrated weed management, mechanical, allelopathy, bio-herbicide, sustainable agriculture

1. Introduction
Sustainable food production requires shifts in farming practices toward more holistic approaches that better integrate the interactions of agroecosystems' environmental, economic, and social components. Weed science researchers, critical to agricultural productivity, must continue to move forward by engaging in complex issues collaboratively with other scientific disciplines (Lamichhane *et al.*, 2016) [1]. Weeds *are* unwanted plants that thrive in agricultural areas and destroy crops by preventing their seeds from germinating, stunting their growth, and reducing their harvest. Thus, weed management in the early growth period deserves serious attention from farmers, plant scientists, breeders, and extension workers immediately. Weed management is imperative for sustainable agricultural production since it dictates whether crops are going to realize their full potential for yield or not. The mineral fertilizers and the agro-chemical plant protection products mechanized large-scale agriculture in the industrialized countries. Herbicides or continual tillage are necessary to keep the weeds in check, both of which have severe impacts on the environment and on agricultural production (Bajwa, 2014) [2]. The ultimate outcome will be environmental pollution. Herbicide pollution can also harm soil biodiversity, natural vegetation, non-target crops and human health impact. There is a pressing need in agriculture today for a weed management paradigm shift that is ecologically sound and perhaps radically unconventional. Literature on weed demography and population dynamics in crops and cropping systems, and in diverse habitats, already includes much of the information required to address this necessity. Factors relating to weed ecology and physiology, and interactions between weeds and crops, are preponderant (Patel and Gangwar,) [3]. When both crops and weeds are regarded as part and parcel of natural ecosystems, weed management should become a unified management of weed/crop agroecosystems.

These are areas where these methods will eliminate these problems and will provide longer-lasting solutions for weed management: herbicide resistance, pollution, weed invasion, weed diversification, and yield losses (Gill *et al*., 2024; Westwood *et al.*, 2018) [4, 5]. This is also facilitated by these approaches, in designing integrated weed management (IWM) plans, which further can be expanded for advancing weed science's eco-physiological and evolutionary bases. The "use of technological advancement" and the "many little hammers" idea are two important parts of IWM that are currently starting to make waves (Storkey *et al*., 2021) [6].

Thus, modern weed management still uses the old definition to prevent weed infestation from triggering economic losses of crops; it views any unwanted plant or plant population in a given crop field as a weed. Even though it may sound simple, weed control, under IWM encompasses extensive research and planning, which involves the grounding of scientific facts with experience in real situations. It is not possible to choose the appropriate combination of agrotechnical measures for IWM (Integrated weed management) since weed damage is usually the consequence of an interaction between many species (Scavo & Mauromicale, 2020) [7]. Furthermore, weeds will always be there, year in and year out, since the seedbank is persistent no matter what efforts are put into place to stop or cure them. In the gradual process of application, IWM seeks to maintain the relative competitiveness of crops over weeds during the growing season using current conventional and contemporary management alternatives. Non-chemical approaches are aimed at enhancing the relative competitive ability of crops with weed germination control and weed density reduction in crops. One of the means to long-term weed control is reducing the hazardous influence of agrochemicals on human and environmental health, weed resistance, invasive weed spread, weed shifts, and so on (Sardana *et al.*, 2017) [8].

2. Characteristics and effects of weeds

2.1 Weed fast seedling and the ability to reproduction when young: The ability of weed species to thrive and reproduce depends on their ability to grow and develop as plants. A major competitive advantage for weeds can be provided by their rapid establishment, growth, and reproduction rates compared to crops and other attractive plants. Like Redroot pigweed (*Amaranthus retroflexus*) can flower and produce seed when less than 8 inches tall. Crops cannot do either and *Phyllanthus niruri has* faster growth in groundnut (Singh *et al.*, 2020) [9].

2.2 Twin modes of reproduction: The majority of weeds bear seeds and are classified as angiosperms. Leafy spurge (*Euphorbia esula*), quackgrass (*Eltrygia repens*), field bindweed, and Canada thistle are just a few examples of the many plants that can reproduce vegetatively. One way that *Cyperus rotundus* might spread is by means of tubers.

2.3 Environmental softness: Weeds can tolerate and sometimes succeed in a wide range of environmental and edaphic situations. Weeds can tolerate adverse field conditions because they are capable of modulating seed production and growth with changing temperature and moisture availability. Compared with most of the crops around them, they germinate on soils that have either low, moderate, or high levels of moisture, grow very fast, and begin to produce seed earlier than most crops. Their growth time is similarly very short. Ragus spinosus is able to sprout even in soils that are very acidic (E. Korres *et al*., 2019) [10]**.**

2.4 Self-compatible: Plant reproductive strategy is one of the most critical factors underlying a species' success and ecological adaptation. Weeds are notoriously invasive and persistent in agroecosystems, and they are unusually reproductively flexible. One of the features that makes them so flexible is self-compatibility, or the ability of many weed species to self-pollinate (Esposito *et al*., 2021) [11]. According to Sen *et al*., (2022) [12] Self-compatibility in weeds offers several advantages that facilitate their spread and establishment in new environments. First, self-compatible weeds can reproduce and set seeds without the need for self-pollination or cross-pollination, allowing them to rapidly colonize and thrive even in ears with limited pollination activity.

2.5 Resistant against environmental: Reduced yields and biodiversity are two outcomes of weeds' competition for water, nutrients, and sunlight with native plants and crops in both agricultural and natural settings. The yearly global economic losses attributed to weeds are projected to reach in the thousands of billions of dollars. Additionally, weeds can degrade natural ecosystems and streams, which is a bad effect on the environment (Patel and Kumbhar 2016) [13].

2.6 Dormancy: In order to avoid harsh conditions and germinate when circumstances are favourable for survival, weed seeds go through several types of dormancies or dispersal. In order to germinate, many weeds do not need any particular conditions. There is a larger window of opportunity for weed seeds to germinate than for other types of seeds.

2.7 Allelopathy: Plants exhibit allelopathy, which is the capacity of some organisms to create chemicals that stunt the development of other organisms in their immediate environment. Allelochemicals are a class of specialized metabolites that can affect plants in a variety of ways, typically affecting more than one physiological activity (Moh *et al*., 2024) [14]. According to Gross, (2003) [15] the inhibition of photosynthesis in competing primary producers is a frequently observed mode of action for aquatic allelochemicals.

3. Mechanical weed control:

Depending on the agricultural system and the region, the potential for automated weed control can be quite different. One type of crop that benefits greatly from automated weed management is high-value conventional and organic horticultural crops. The absence of authorised pesticides for these crops and the heavy reliance on human labour for weeding are the main causes of this problem. A prime target for automated weed control systems are fresh market vegetable crops due to their year-round planting in tiny areas (Fennimore *et al.*, 2014) [16]. As an alternative to mechanical weed control, precise weed management and thermal weed control methods have the potential to be highly effective (Travlos, 2013) [17].

3.1 Automatic Weed control: Weed management forms part of contemporary agricultural practices. The chemical herbicides used to rid a farm of weeds and weeds controlled manually have their problems: they are associated with expensive labors, risks to the environment, and potential development of herbicide-resistant weeds (Du *et al.*, 2021) [18]. Alternative methods of weed control, such as those involving autonomous robotic devices, are attracting more and more attention (Scavo & Mauromicale, 2020) [19, 7]. These planters make use of a disc blade in the shape of a semicircle that can spin at different speeds. In order to avoid damaging the transplanted crop, a computer-controlled guiding system and a camera work together to dynamically alter the disc's spinning speed. Compared to the conventional cultivator, the weed density is 30–54% lower when using the rotating cultivator. Thin and weeding a lettuce crop with the latter method takes 16-31% longer than using the rotary cultivator (Tillett *et al*., 2008) [20]. As technology advances, robotic weed control systems will be able to do the following: detect weeds, store and analyze that data, help decide when and where to control weeds, deploy the robot to control weeds, and finally, measure the treatment's effectiveness to evaluate the decisions made. Some examples of weeders that are now on the market include basket weeders, brush hoes, powered vertical axis tines, finger weeders, torsion weeders, mini-ridgers, rotating wire weeders, pneumatic weeders, and spring tine harrows (Merfield, 2016) [21].

3.2 Robotic weed control: It is a robotic weed management process based on four steps: guidance, plant identification, accurate weed removal, and mapping of weed species (Young *et al*., 2013) [22]. A dependable decision-support system, effective weed-sensing tools, efficient and proper robotics, variable-rate application technology, and robotic efficacy are five key elements that must be developed for an effective robotic weed management system. The NIR stereovision system provided sufficient machine guidance, calibrating the device to detect the weed in cereals Implementing a weed-free zone. Climate, agricultural practices, regional topographical differences, and cropping systems directly influence the accuracy of machine vision. Morphological, spectral, and visual texture attributes are the very bases of detection. Morphological features of weedy plants may have potential factors for identification by machine vision, especially when their differentiation from desired vegetation is attempted**.**

Application of convolutional neural networks in weed species identification and growth stage estimation is relatively new. Light reflectance has worked well as an indicator with machine vision in weed detection. Following weed recognition and the computer directions, the next step will be to have robotic weed removal with pinpoint accuracy (Mierau *et al*., 2020) [23]. Weeds can be removed mechanically, chemically, thermally, or electrically by use of robots. Future best integrated weed management may use robots in sensor and plant recognition technologies, in automated robotic weed control (young *et al*., 2013) [22].

3.3 Thermal weed control: There are two major groups of thermal weed control methods, which may be classified in relation to the mode of action. Direct heating techniques such as steaming, flaming, infrared weeders, hot air, or hot water. Indirect heating techniques like electrocution, microwaves, laser radiation, or UV-light. Cryogenic procedures may be regarded as a kind of thermal weed control.

3.3.1 Weed control by hot water and hot foam: An environmentally-friendly alternative to herbicides chemical herbicides have long been the dominant method for controlling weed. Most annual weeds and many perennial weed species can be effectively killed by applying hot water. Warm water Weed control devices are also part of weed control. On the other hand, there are no side effects of hot water treatment method; it is safe unlike flame weeding or radiation methods. Effectiveness of hot water treatment is greater on has a dense weed population due to the high penetration ability of the plant canopy (Hansson & Ascard, 2002) [24]. Since hot water is not a selective weed killer, it is ordinarily reserved for non-farming areas. This method finds application within European precision weed management programs due to the higher success realized. Based on the fact that foam breaks down more slowly and more of the heat is transmitted to the plant being targeted for destruction, use of hot foam is more energy efficient than using hot water.

3.3.2 Weed control by steam: An alternative to hot water for weed management that is faster, more effective, and more environmentally friendly is steam. This is particularly true for weeds growing on hard surfaces. Specifically, soil steaming eliminates pests and diseases that are carried by the soil as well as weed seeds. Soil steaming kills weed seeds up to 20 cm deep, reducing the weed seedbank even more than the stale seedbed strategy: letting weed seeds mature and then killing them before crop planting with only minimal soil disturbance (Bauer *et al*., 2020) [25]. It is not as expensive as chemical fumigation, yet it is certainly not as cost-effective as other non-chemical preventive strategies. Steaming can also be done in a "banded treatment," only treating the region within each row prior to planting, further reducing the energy use. Again, unlike methods such as solarization, which require long periods of time and specific environmental conditions, soil steaming achieves tangible results in a short frame of time. This is in contrast to chemical fumigation, which needs the plants to have about a 15–30-day window between applications before planting. Steaming, however, has no lingering effect, so seeds or transplants can be done as soon as the soil reaches room temperature (Fennimore & Goodhue, 2016) [26]. The weed flora would determine the heating depth. Since the majority of the seeds in the soil seedbank are from weed species, which have tiny seeds that germinate in the top 0-20mm of soil, steaming to a moderate depth of 50-60mm should be enough. Important biological components for the advancement of band-steaming technology have been the subject of a number of laboratory investigations (Melander and Kristiansen, 2011) [27].

3.3.3 Weed control by flaming: The process of flame weeding makes use of a fuel-burning tool, which can be either attached to a tractor or used independently, to generate extremely high temperatures. One such method for controlling weeds in crops is flame treatment. Intracellular water expands and cell membranes denature in response to brief exposure to high heat, resulting in cellular leakage, dehydration, and eventual cell death. Exposure to generally destroy leaf tissue lasts up until 130 ms. There were estimates by the studies that a 1-second exposure to flame temperatures between 800 and 1000 °C killed the weeds (Hoyle & McElroy, 2012) [28]. Among organic farmers, flame-treating has become the most widely adopted thermal technology of weed control. Weed management preceding measures include burning, pre-emergence, as part of the stale seedbed strategy. Quite a number of benefits come by using flame weeding as opposed to conventional measures of weed management. Hand weeding is a lot less expensive compared to burning. In heat-tolerant agronomic crops such as corn, cotton, and sugarcane or when the flame is directed toward the base of the crop to control weeds inside the row, there is minimal risk of root damage to the crop (Horesh *et al*., 2019) [29].

3.3.4 Cryogenic weed control: One form of thermal strategy is to apply a cryogenic material to the seeds or the seedlings of weeds: cryogenic weed control. Cryogenics-based substances can produce extremely low temperatures. Cryogenics materials include carbon dioxide snow (CO_2: ~78 °C) or liquid nitrogen (LN2: ~196 °C). Mechanical compaction pressure after sufficient exposure of the vegetation will assist in macerating the flash-frozen tissues. Applied to snow or ice-covered ground, cryogenic compounds such as magnesium chloride-6-hydrate, sodium chloride, ammonium nitrate, or calcium chloride-2-hydrate can reduce weed germination since weeds absorb these molecules (Yadav *et al*., 2011) [30]. There are specific species that are more responsive to cold action in the case of weeds. Thus, by freezing treatment alone, weeds will not go out completely. Although the effectiveness of cryogenic weed management techniques within agroecosystems has been mixed, they hold potential. In weed control, such a technique as cryogenic weeding is significantly more energy-intensive compared with the rest of the thermal techniques. A reduction in energy use, improved application technology, and favoring the application parameters might improve the environmental compatibility of the cryogenic weed control systems (Spagnolo *et al*., 2019) [31].

3.4 Weed control by electrocution: Electrocution refers to the method of weed control that involves the use of electric shocks. Spark discharge or electrical contact with 20 kV can kill weeds, according to data, however there hasn't been enough research on this. reports that there has been a noticeable uptick in the usage of electrophysical engineering and high-electric power to effectively eradicate unwanted plants with little use of chemical pesticides (Lati *et al*., 2021) [32]. The effectiveness of electrocution depends on electric shock intensity, contact or exposure length, weed species, morphological features, and growth stage. Drought increases the damage. However, this technology is not applied in agriculture due to greater energy requirements and high financial expenditures, not to mention dangers to the operator. Maybe this technology will find an application in organic growing systems of vegetables and orchards (E. Korres *et al*., 2019) [10].

3.5 Weed control by abrasive grit: The use of air-propelled organic grits to abrade the tissue of small weeds was proposed. In greenhouse and field experiments, grits derived from crop residues, such as corncobs or walnut shells, were shown to be effective in controlling small weed seedlings. This suggests that additional tools, particularly for organic cropping systems, are needed for efficient integrated weed control. Applying grit at the right time is crucial for weed management; studies have shown that it works best between the one-and five-leaf phases of corn development, or between the one-, three- and five-leaf stages (Lati *et al*., 2021) [32]. The maize yields were comparable to the controls that were hand-weeded and did not use abrasive grit. Wortman (2015) [33], reported applying air-propelled granulated walnut shells, maize cobs, greensand fertilizer (i.e., pelletized poultry manure), and soybean meal reduced weed biomass in tomato and pepper (Capsicum annuum) cropping systems by 69-97% compared to the weedy control. Tomato yield increased by 44% and pepper yield by 33%. The abrasive grit's estimated contribution to crop fertilization, which ranges from 35 to 105 kg N ha^{-1}, further enhances the method's practicality and economic viability. One ideal development in crop production systems would be to find new uses for agricultural wastes and crop leftovers, such as weed management, in a manner that would increase the efficiency of resource use while reducing the environmental impact.

4. Agronomic/cultural weed control: Cultural weed management necessitates the abandonment of numerous antiquated practices. The goal should not be eradicating all weeds, but rather minimizing weed-crop competition and weed establishment throughout the early stages of growth (Blackshaw *et al*., 2007) [34]. As a cost-effective and eco-conscious option, weed control using agronomic and cultural approaches has gained a lot of support. The most important cultural weed management strategies are adjusting the planting time and irrigation system, cultivating crops with increased weed resistance, using mulch, cover crops, and intercropping (Rosset and Gulden, 2020)[35]. When it comes to weed management, it's crucial to choose the right crop variety, use healthy seeds, ensure uniform germination, plant at the optimum depth, consider the weather, and choose an appropriate planting pattern (Mierau *et al*., 2020) [36].

The main cultural control methods currently used by farmers and weed scientists to improve. Listing the things below, weed control and management are included (Patel, 2023) [37].

4.1 Crop rotation: Thus, if you want to stop weeds from becoming associated with a certain crop, try rotating crops with diverse growth cycles. To use this method, one can alter planting times and employ other cultural practices, doing so will decrease weed-crop competition and severely hinder weed establishment. Hunt *et al*., (2017) [38] reported Some crops have a tendency to attract weeds because their life cycles and growth rates are comparable, according to a number of studies.

4.2 Crop competition and cultivar selection: Reduced weed-crop competition is necessary because weeds will always outcompete the primary crop for resources like water, nutrients, and space. Increased copula competition with invasive weeds is possible in field plot soil rhizospheres when crops are able to suppress weeds, slow their growth, and lower their seed bank (Mayerová *et al*., 2018) [39]. At the same time, the crop should be productive and stable in its production while growing fast and competing with weeds. Reports for the competitiveness of different genotypes in a crop against weeds have been noted earlier in several reports. The best course of action, based on available knowledge about weed life cycles (tall, dwarf), favors a taller genotype with a greater competitive ability with weeds for the benefits we seek (Datta *et al*., 2017) [40].

4.3 Planting pattern: The crop-weed competition is heavily influenced by the planting pattern. One strategy to give the crop an edge over the weed is to plat it early on. Here, the primary crop will sprout before the weeds do, and it will be able to prevent the weeds from growing by blocking their sunlight (Mahajan *et al*., 2017) [41]. On those lines, increasing the planting density and reducing the spacing between the rows will favor the crop in competitive ability against weeds (Andrew and Storkey 2017) [42].

4.4 Fertility manipulation: Indirectly affecting weed development and population dynamics, fertilizers application can change the nutritional status in the agro-ecosystem (Kaur *et al*., 2018; Ekwangu *et al*., 2020) [43, 44]. Weeds are heavy users of nitrogen; thus, it stands to reason that nitrogen fertilizers would have the opposite effect and encourage weed growth. Consequently, to lessen the weed interference with crops, it is important to utilize nitrogen fertilizers wisely in terms of application method, timing, and dosage (Maqbool *et al*. 2020) [45].

4.5 Allelopathy: It is the process by which, in natural as well as managed ecosystems, one plant species or microorganism influences the development, growth, or reproduction of another plant species or microorganism. For generations, farmers have exploited these allelopathic phenomena for their benefit by lessening weed infestations without having a full knowledge of its molecular mechanism. Again, with the advent of herbicide-resistant weeds, allelopathy is being reconsidered as a pesticide alternative. On the list of many allelochemicals are terpenes, alkaloids, phenols, sugars/glycosides, and non-proteinaceous amino acids. Sustainable weed management options include plants having allelopathic potential, which reduce the need for herbicides. Plants with allelopathic potential may be considered viable alternatives to herbicides for weed control as a means of reducing the selection pressure for herbicide resistance. Allelopathic plants have the ability to discover new herbicidal chemicals with novel MOAs. Incorporating allelopathic crops into crop rotations, using their residues for cover cropping, and selecting the most active allelochemicals for use as bioherbicides are three ways in which agroecosystems can manage and utilize allelopathic mechanisms for weed management Table 1 of course, they're not very successful on their own, but they work wonders when integrated into an IWM plan. Add an allelopathic crop into your rotation, and it'll kick in to counter autotoxicity, reducing pest pressure while amplifying all the below-listed benefits.

According to (Macías *et al*., 2007) [46] In recent years, one of the most prominent areas of allelopathy has been the selection of active allelochemicals for possible application as bioherbicides. Dayan *et al*., (Dayan *et al*., 2012) [47] reported advantages and disadvantages compounds derived from bioherbicides. The most active allelochemicals include phenolics (e.g., vanillic acid, p-hydroxybenzoic acid), flavonoids (e.g., kaempferol, quercetin, naringenin), coumarins (e.g., umbelliferone, esculetin, scopoletin), cinnamic acid derivatives (e.g., chlorogenic acid, ferulic acid, caffeic acid, sinapic acid, p-coumaric acid), coumarins, and sesquiterpene lactones (e.g., artemisinin, centaurepensin, cynaropicrin) (Scavo *et al*., 2018) [48].

Table 1: Allelopathy for sustainable weed management

Allelopathic source	Target weed	References
Glycine max (L.) Merr., *Triticum aestivum* L.	*Setaria faberi* Herrm	(Alsaadawi *et al*., 2012) [49]
Vigna mungo (L.) Hepper	*Echinochloa colona* (L.) Link, *Digitaria sanguinalis* (L.) Scop, *Setaria glauca* (L.) Beauv.	(Alsaadawi *et al*., 2012) [49]
Sorghum bicolor (L.) Moench	*Cyperus rotundus* L., *Trianthema portulacastrum* L., *Cynodon dactylon* (L.) Pers., *Convolvulus arvensis* L., *Dactyloctenium aegyptium* (L.) Willd., *Portulaca oleracea* L.	(Cheema *et al*., 2004) [50]
Brassica nigra L.	*Avena fatua* L	(Jabran *et al*., 2010) [51]
Juglans nigra L.	*Conyza canadensis* (L.) Cronquist, *C. bonariensis*, *P. oleracea*, *Ipomoea purpurea* (L.) Roth	(Shrestha. 2009) [52]
S. bicolor, *Helianthus annuus* L., *Brassica campestris* L.	*T. portulacastrum*, *C. rotundus*, *Chenopodium album* L., *Cronopus didymus* L.	(Jabran *et al*., 2010) [51]

4.6 Cover crops: A weed control method called cover crops or subsidiary is applied during the off-season in farms to cover the surface of the farm and ensure enough supply of nutrients for the next season. According to Korres, (2018) [53] any crop can be used as a supplementary crop and cover crops are probably one of the most significant means to achieve better soil health from the chemical, physical, and biological sides, as well as to repress weed growth in the period of cover crop growth. Crops such as hairy vetch (*Vicia villosa*) and cereal rye (*Secale cereale*) very often cover the soil uniformly and densely, while crownvetch (*Coronilla varia*) is equally good for long-term management of the soil (Price and Norsworthy, 2013) [54]. The following crops could also serve as cover crops: red clover (*Trifolium. pratense*), white clover (*Trifolium. repens*), crimson clover (*Trifolium incarnatum*), peas (*Pisum* spp.), bird's-foot trefoil (*Lotus corniculatus*), common oat (Avena sativa), ryegrass (Lolium spp.), fescues (*Festuca spp*.), meadowgrass (*Poa* spp.*)*, smooth bromus (*Bromus inermis*), thimeum pratense, orchardgrass (*Dactylis glomerata*), and fescues *(festuca* spp) (Korres, 2005) [55]. Amongst winter crops, winter cereals this includes high biomass production, hence excellent ground cover, such as cereal rye, which offers efficient weed control (Schomberg *et al*., 2006) [56]. The key reasons to recommend cover crops for weed management are prevention of weed emergence through physical suppression, and reduction of light transmission either by producing high biomass or generating allelochemicals (Saini *et al*., 2006) [57]. Some of the desirable characteristics of a cover crop are fast germination and seedling growth, vigorous seedlings, tolerance to weather extremes, easy termination and management, and competitiveness (Akbari *et al*., 2019) [58].

5. Bio-herbicide use for weed control

Bioherbicides are an all-natural way to control weeds; they are composed of microorganisms like pathogens and other bacteria or phytotoxins found in insects, plants, or insects themselves. According to Bailey (2014) [59], bioherbicides are products of natural origin that could be used in controlling weeds because bio-herbicides comprise of chemicals available in nature doesn't guarantee they are harmless. Natural phytotoxins can thus be toxic not only to non-flora species in the environment but also to specific bacteria, viruses, and fungus that infect animals and people. Therefore, these natural toxins must be carefully managed to this is to avoid any unintended impact on the crops or other fauna and flora (Duke *et al*., 2000) [60].

5.1 Bioherbicide extract from plant: An alternative means of bioherbicides development for sustainable practices in weed management that can be up-taken in agriculture can be through plant extracts that have been in use for a long period of time either as a source of nutrition or medicinal purpose. Bioherbicides developed out of plant or animal extracts have shown some satisfactory control of weeds. No harm comes to crops by using some chemicals found in plant extracts, which have a specific inhibitory action against weed growth (Salama *et al*., 2014) [61].

Perhaps the weeds are more sensitive compared to the target enzymes, or perhaps the weeds have special receptors capable of receiving the chemicals and reacting accordingly Hosni *et al*., (2013) [62]. Some plant species exude alcohols, fatty acids, phenolics, flavonoids, terpenoids, steroids, and a few other allelochemicals. These compounds inhibit the formation, growth, and reproduction of nearby flora, including weeds.

5.2 Bioherbicides from allelochemicals: Compared to synthetic chemicals, allelochemicals nature's own herbicides have a number of advantages. Allelochemicals have a wide variety of chemical structures; some of these structures could be useful as building blocks for herbicides. Not all-natural substances include halogens, and some are water-soluble. They are environmentally safe since their half-lives are short compared to synthetic herbicides. Dayan and Duke, (2014) [63], reported the following three methods of obtaining natural products for herbicides: (i) isolation of pure compounds from other laboratories; (ii) preparation from previously unexplored biological material; (iii) selection of herbicidal material guided by ethnobotanical and/or chemical ecology information. Plant allelochemicals have, over the years, been used in the discovery of many herbicides like Cinmethylin, Mesotrine, Artemisinin, Biolaphes, Glufosinate and Dicamba. Indeed, in-depth research shows that phytotoxic compounds from plants might represent an important strategy of integrated weed management (Xiao *et al*., 2017) [64].

Table 2: Bio-herbicide and their respective source with target weed.

Source	Target weed	References
C. purpureum	*Populus euramericana Guinier*	(Stewart-Wade *et al*., 2001) [65]
B. napus	*Amaranthus retroflexus* L.	(Muñoz *et al*., 2020) [66]
Citrus sinensis (L.) Osbeck	*Solanum nigrum* L	(Verdeguer *et al*., 2020) [67]
Citrus limon (L.) Osbeck	*D. sanguinalis*	(Verdeguer *et al*., 2020) [67]
Cymbopogon citratus (DC.) Stapf	*Euphorbia spp.*	(Avila-Adame *et al*., 2008) [68]
Phytophthora palmivora	*Morrenia odorata* (Hook. &Arn.) Lindl.	(Tateno, 2000) [69]
Alternaria cassiae	*Cassia obtusifolia* L.	(Tateno, 2000) [69]
Phoma macrostoma	*Reynoutria japonica Houtt*	(Mendes and Rezende, 2014) [70]
Streptomyces acidiscabies	*Taraxacum officinale* L.	(Mendes and Rezende, 2014) [70]
Alternaria destruens Chondrostereum	*Cuscuta spp.*	(Bailey, 2014) [71]

6. Integrated weed Management:

6. Integrated weed Management: Increased demand for food, due to a rising population, can be met through a more sustainable strategy that makes responsible use of land and water, enhances food diversity, and boosts agricultural yields. This means that a reliance on chemical weed control alone is unsustainable in view of the long-term impact of the herbicides and their residues on the environment, combined with the natural increase of weed populations and their herbicide resistance (Mace *et al*., 2007) [72]. There is no one perfect method of weed control, and therefore, combining weed management strategies is best for effective control. Development of new cropping systems utilizing the minimum amount, of herbicides in controlling weeds by applying what is currently known about the effects of agricultural practices on weed populations is another option. Integrated weed management strengthens weed management principles that have proved to be most effective in controlling weeds over the long term through cultural, mechanical, thermal, and chemical methods based on an ecological approach (Moss, 2010) [73]. One of the goals of integrated weed management is to maintain the weed population below an economic threshold level, through reduced emphasis on eradication strategies and promote a strategy of containment for potential increases in weed diversity. Its effectiveness depends on the balance between characteristics of the weeds present with the management tools available to growers. Weed balance between. Long-term deterioration of communities and management tools could result if attention is not given to management of weeds at landscape level, and to preservation of herbicides and ecological control tactics in the face of evolutionary response of weeds (Patel *et al.*, 2024) [74]. Management of weeds over large areas and long periods of time requires an expanded perspective on weed community dynamics and weed evolution.

7. Conclusion

Weeds are the most significant biotic factor of reduced productivity of crops in agroecosystems. The current status has IWM being widely used, especially in organic farming and other low-input agricultural techniques, due to an increasing demand for weed control methods that are environmentally harmless and economically feasible. Herbaceous field crops can't be grown without the aid of herbicides. The holistic approach is needed for integrating various tactics for reduced reliance on chemical tools: stale seedbed, weed thresholds, combined direct methods, soil solarization, controlled pest and water management, herbicides, etc. Even after a period of time, environment and socioeconomics are going to change, so IWM has to be responsive also. Research is needed to underpin the design of long-term experiments, regulations and incentives, and to reduce the challenge of integrating radically disparate control systems. Although they maybe They may not be well accepted as individual methods of weed control but in combination with other by agrotechnical measures, they could ensure systematic ways of providing sustainable and reliable weed control, especially in organic production and small farming systems. Long-term weed control shall be simple, flexible, safe, and effective, while at the same time being. It will be integrated into IWM practices, depending on weed diversity and density.

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