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Review

Challenges and Alternatives of Herbicide-Based Weed Management

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Abstract: Weeds are the most severe and widespread biological constraint on agricultural production systems and cause damage to cropped and non-cropped lands. They reduce crop yield and degrade the quality of the produce, besides raising the cost of production. The intensification of agriculture in the Green Revolution era attracted chemical fertilizers and dwarf varieties coupled with mono-cropping and irrigation practices, which enhanced crop-associated weeds and the widespread use of herbicides for easy control. Pesticides may kill many organisms, both target and non-target species, in the environment, causing an imbalance in the ecosystem. Despite the significant increase in productivity, the environmental repercussions of industrial agriculture, characterized by the use of high-yielding crop varieties and the extensive application of chemical fertilizers and pesticides, have prompted a quest for more sustainable agricultural practices worldwide. One potential alternative lies in innovative approaches that draw upon ecological insights gleaned from studying natural ecosystems. These approaches aim to create “ecologically intensive” agro-ecosystems. Developing ecologically intensive agro-ecosystems necessitates a deep understanding of the biological dynamics within ecosystems and the integration of traditional agricultural knowledge held by local farmers. Considering the potentiality of appropriate weed management technologies to substantially improve crop productivity, there is an opportunity for the development, popularization, and adoption of effective, economical, and eco-friendly weed management technologies.

Keywords: ecological approach; ecotoxicology; herbicides; integrated weed management; sustainable agriculture

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1. Background

The indirect effect of industrial development in Europe led to herbicide-based weed management, wherein possibly the industries wanted to sell their by-products as herbicides while also pulling human resources from farms to factories [1–3]. The discovery of 2,4-D in 1941 was the leaping move in herbicide-based chemical weed control [4]. For the first time, farmers were able to control many broadleaf weeds selectively and inexpensively in cereals without obvious harm to the crop. Amitrole was patented as an herbicide and plant growth regulator in 1954 [5]. As a result, inexpensive herbicides made farming more efficient, as farm labor requirements were reduced for weed management. Later, the discovery of glyphosate in 197, led to the large-scale adoption of herbicides due to their broad-spectrum post-emergence control of annual and perennial weeds [6]. The use of glyphosate-based herbicides has increased by approximately 100-fold from the late 1970s to 2016 because of their widespread application in cropped and non-cropped areas [6]. Herbicides became common in agrochemical-based agriculture, especially when herbicide-tolerant crops became popular in some countries [7]. This increased the proportion of herbicide use in the overall pesticide load in arable crops [8]. The herbicide solution evolved as rapidly as the new weed problems needed solutions. These solutions were often influenced by agrochemical industries. However, the proper use of herbicides is not always practiced, leading to several challenges, such as herbicide resistance or cross-resistance [9]. It has been observed that a single weed control method is not sustainable and effective in the long run.

There has been a great advance in productivity and soil conservation promoted by the use of agrochemicals such as glyphosate in conservation agriculture systems such as direct seeding, which is widespread throughout the world [10]. Although chemical weed management took a prime place in post-green revolution agriculture, since the 1980s, weed researchers have gradually shifted from screening new herbicides toward an ecological approach as long-term solutions rather than quick fixes [5], especially after knowing the challenges of herbicide resistance [11]. Scientists and researchers put more emphasis on understanding weed-related issues for establishing an effective weed management strategy, including a focus on sustainable agriculture. As awareness towards the conservation and enrichment of ecologies and the environment grows, cleaner weed management technologies are being developed [11]. Further, concerns about herbicide resistance and environmental pollution development of organic agriculture have forced scientists to search for innovative non-chemical integrated solutions using vigorous cultivars, conservation agriculture, crop diversification, crop rotation, cover crops, appropriate nutrient and water management, and integrated weed management [12–15]. However, the challenges are still related to the non-availability of labor and mechanical tools; inadequate information on weed biology, shifts in weed flora, herbicide-resistant weeds, lack of understanding of the impact of climate change on weeds and weed control, popularizing integrated weed management with herbicide use by ensuring safe use to avoid adverse effects on human health and the environment, avoiding weeds developing herbicide resistance, and preventing entry and management of alien invasive weeds. With appropriate sustainable intensification technologies, herbicide use can be significantly reduced.

2. Negative Consequences of Chemical Weed Management

2.1. Toxicology

Herbicides are being used to control weeds in crops (field, vegetable, and plantation crops) and water bodies, and also to clear unwanted vegetation in grounds, parks, industrial sites, and railway embankments. Likewise, smaller quantities of herbicide are also being used in forestry, pasture systems, and the management of areas set aside as wildlife habitats. Proper use of herbicides leads to higher crop productivity, but non-judicious use may lead to higher residues in crops, soil surface contamination, and groundwater contamination [16]. Over the years, herbicide use has increased tremendously, mainly due to an increase in labor costs and non-availability, the selectivity of herbicides, the spectrum of herbicides, and effective and efficient weed control [16]. Therefore, much research has been carried out to develop newer, safer, and more cost-effective herbicides with different modes of action. However, the non-judicious use of herbicides is a major concern and causes shifts in weed flora, nutrient imbalance, residues in soil, and contamination in crop production [16].

It has been recorded that the majority of the herbicides are being used non-judiciously (high dose, improper methods, equipment, spray volume) by the growers; this alters plant growth, physiology, and metabolism and ultimately results in phytotoxicity and impaired crop productivity [16]. Herbicides have their own mechanism of showing phytotoxicity symptoms on plants; however, in general, it can be visualized by leaf and shoot malformation, root and shoot stunting, leaf spot, leaf chlorosis (yellowing), and leaf necrosis (death), as summarized by Strange [17]. These phytotoxicity symptoms appear on plants when herbicides are used either at higher doses or improperly at the wrong stage of crop growth (Figure 1).

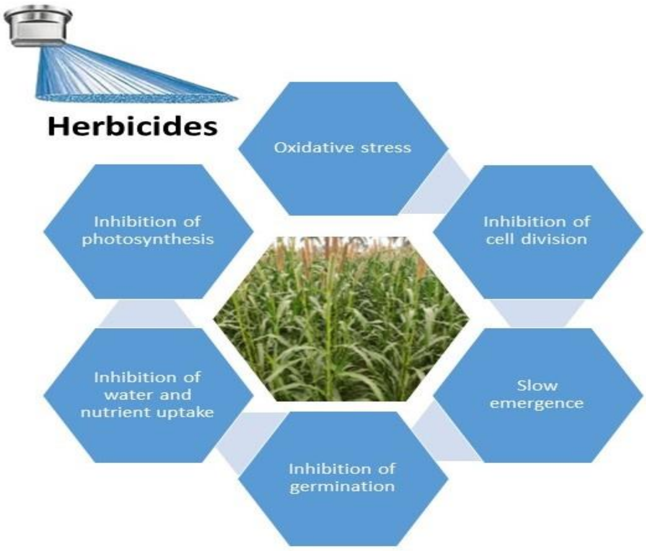

Figure 1. Herbicide-induced phytotoxicity on crop.

2.2. Herbicide Residue(s)

Herbicides may have advantages with judicious application; however, improper use may cause residue problems, phytotoxicity to crop plants, residual effects on succeeding or susceptible crops, or non-target organisms [18]. The continuous use of similar types of herbicides over the years may accumulate in produce, soil, and groundwater, which can lead to health hazards [18]. Through bioassay, certain sensitive crops have been used to sense the presence of herbicide residues below a detectable level [19,20]. Herbicide persistence in the soil is expressed as the half-life or time required to degrade fifty percent of the original molecule (Table 1). In fact, during the optimization of the chemical structure, minimizing the residual effect on the soil and crop production is taken into consideration, such as high crop safety, labor savings (broad spectrum, wider application window, and longer residual activity), low environmental impact (low dose, low water solubility, and low downward mobility to prevent groundwater contamination), and low mammalian and fish toxicity.

Table 1. Half-lives of some herbicides in soil [21].

Herbicide	Half-Life (Days)	Toxicity Class Based on LD50
Atrazine	13–58	III
Butachlor	5–24	III
Fluazifop-p-butyl	8–24	III
Fluchloralin	12–46	IV
Dithiopyr	11–25	IV
Imazethapyr	57–71	IV
Isoproturon	13–21	III
Chlorsulfuron	31–93	IV
Chlorimuron	60	IV
Flufenacet	9–22.5	V
Metribuzin	23–49	III
Metolachlor	8–27	III
Oxyfluorfen	12–29	III
Pendimethalin	15–77	IV
Pretilachlor	10–11	IV
Sulfosulfuron	3–27	IV
2,4-D	7–22	II–III
Metsulfuron-methyl	70–147	IV
Thiobencarb	19–24	III
Pyrazosulfuron-ethyl	16–21	IV

2.3. Herbicide Persistency and Degradation in the Soil

Once herbicide is applied to the field, its half-life is not absolute because its degradation is largely dependent on the soil type, temperature, and concentration of the herbicide applied. Alongside herbicide chemistry, prevailing soil conditions during and after the application, as well as application technology, influence the fate of the herbicides in the soil [22]. Likewise, frequent and continuous rain may cause more leaching and runoff. Among soil types, sandy soil (lower CEC) has a higher leaching potential than clayey soil [23]. Chemical degradation by redox reactions is common with anilines, dinitroanilines, and phenols. Hydrolysis, ester formation, and oligomerization/polymerization reactions are catalyzed by clay surfaces, as are photolysis reactions that are common with bentazon, fluchloralin, and olefins. Based on previous research, it has been reported that herbicide residues are present in/on crops, soil, water, and the food chain. The occurrence of fluazifop-p-butyl in soybean [24], alachlor in cotton [25], benthiocarb in transplanted rice [26], metsulfuron-methyl in wheat and transplanted rice [27], trifluralin in black gram [28], anilophos in grain and rice soil [29], pendimethalin, and trifluralin in celery seeds [30] have been reported under Indian tropical conditions, and in most cases, the residues were found to be safe at harvest.

2.4. Herbicide Resistance

Continuous and repeated use of herbicide(s) with a similar mode of action may lead to the development of resistance in weed biotypes. There are always possibilities that the weed biotypes that developed resistance to a particular herbicide may develop resistance against other herbicides with similar modes of action [31]. The main reason is to have a similar binding site. The evolution of herbicide resistance in weeds could further aggravate yield losses [31]. Presently, herbicides are an integral part of weed management in developed countries; hence, more cases of herbicide resistance have been reported there. The application of sub-lethal doses of herbicides (intentionally or unintentionally) alters the growth, metabolism, and survival of susceptible biotypes, especially in self-pollinating plants such as *Avena fatua* L. (wild oat) [32,33]. Globally, the incidence of herbicide resistance in weeds, the management challenge, and the cost of management are gradually increasing. Herbicide resistance in weeds is not a new problem, as some of the biotypes evolved resistance during the early 1950s [34]. However, in the 1980s, traits associated with herbicide resistance in crops were adopted to combat the weed resistance problem [35,36].

Globally, 523 unique cases of weed resistance have been reported in 269 weed species (154 dicots and 115 monocots) to date. Weeds have evolved resistance to 167 different herbicides in 99 crops in 72 countries, which accounts for 21 of the 31 known herbicide sites of action [37]. Moreover, in just eleven years, 321 unique cases have been added to the list of herbicide-resistant weeds, compared to 195 species in 2010 [31]. In addition, the crisis is more aggravated, as in the last three decades, no innovative chemistry or new herbicide site of action has been discovered or developed [38]. This might be due to the large investment in the development of new herbicide chemistry (>USD 250 million), and more funds have been diverted for the development of insecticides and fungicides. Herbicide resistance development in a short span of time is one of the important reasons for this shift [39–41]. These increased cases of herbicide resistance require concerted efforts to have timely integrated weed management strategies to contain yield reductions for sustainable crop production [39]. Management of herbicide resistance by adopting single management strategies is difficult to achieve [38]. Therefore, diverse weed management tools are needed, considering the obstacles, concerns, challenges, and specific solutions needed for various production systems [42]. Management strategies, regions, cropping systems, and available affordable options play a crucial role in adopting management strategies. Continuous efforts are needed to bring a community-wide interdisciplinary approach to understanding the complexity of managing weeds within the context of the whole farm operation and to communicate the need to address herbicide resistance [32].

2.5. Food Hazards

The US Environmental Protection Agency (EPA) issues guidelines and prepares laws and regulations for the development, distribution, use, and disposal of pesticides. After extensive tests, the US-EPA decides the reference dose for each pesticide for its approval for use and also standardizes the amount of pesticide ingested over time, which is not expected to cause adverse health hazards [18]. Herbicides can cause human health hazards in two ways: Directly through active ingredients and also through commercial formulations often containing other chemicals, including inactive ingredients. The negative effects of some of the herbicides have already been reported, but those are mainly due to the higher LD50 observed against mammals than insecticides [43]. Exposure to contaminated phenoxy herbicides with dioxins increases the cancer risk [44]. The European Commission has restricted the use of glyphosate and also banned one of its co-formulant surfactants, polyethoxylated tallow amine [45].

Continuous and heavy use of herbicides in the same area may lead to adverse effects on bird populations, mainly due to a lack of vegetation and the consumption of contaminated vegetation [46]. Newton [47] reported a decline in the seed-eating bird population in the herbicide-used area. Exposure to low concentrations of atrazine has been reported to cause demasculanization of frogs [48]. Acetochlor decreased soil microbial community diversity [49]. Research conducted at various places showed that continuous exposure to herbicides may lead to the accumulation of residues in different body parts of fish and ultimately result in biomagnifications through the food chain [50–52].

2.6. Water Pollution

Non-judicious use of herbicides may affect the flora and fauna of water bodies. In intensive agriculture, the frequent use of herbicides can reach the nearest water bodies by runoff [53]. After herbicide application, certain quantities may diffuse and percolate downward, which may contaminate the groundwater [54]. A small quantity of these chemicals causes a serious threat to water quality, causing the extreme extinction of water-living organisms [55]. Based on estimations conducted of water bodies, it was reported that 2,4-D, atrazine, and 17 other herbicides active in gradient and their by-products contaminated the water bodies [56]. Likewise, herbicide contamination also influences the algal population, as they are very sensitive to a small quantity of oxadiazon. This can damage the cell, block photosynthesis, and reduce growth. It also influences phytoplankton and zooplankton and causes a serious threat to aquatic biodiversity [57].

2.7. Soil Pollution

Microbes are important living organisms in the soil that regulate soil health [18]. Every microbe has a defined role, such as organic matter degradation, increasing nutrient availability, and maintaining soil properties. Some microbes play an important role in the degradation of toxic substances such as heavy metals or their derivatives, xenobiotics, and pesticides [58]. Contrarily, many of the microbes are severely affected and are detrimental to soil health. Application of herbicide doses, types, frequency, seasonal variation, and weather determine how an herbicide will manipulate microbial diversity and ultimately soil health [59]. Herbicides such as pendimethalin, oxyfluorfen, and atrazine are commonly used pre-emergence herbicides; they considerably influence microbial abundance, activity, and community diversity [60]. Continuous use of metribuzin accumulated on the soil surface hinders the clay formation process, mostly by reducing the microorganism diversity [61]. Application of glyphosate and its derivatives, aminomethylphosphonic acid (AMPA), is toxic, as these are absorbed by organic matter and clay and not degraded by microbes. Continuous use of glyphosate over the years accumulates in soil (more in clay soil) and causes soil toxicity that adversely affects soil microorganisms [62]. Similarly, glyphosate and AMPA are disseminated to adjacent fields or water bodies by various means (soil and water) and affect not only target organisms but also plant communities, humans, or other organisms [63]. The earthworm is another soil health indicator; the presence of the earthworm indicates healthy soil. The application of glyphosate decreases the earthworm population and biomass and disturbs cocoon hatching [64]. The degradation rate of the phenyl rings of herbicides largely depends on the presence and distribution of responsible microorganisms. Degradation of herbicides and their ability to pollute soil remaining within the soil hampers non-target organisms such as plants and microbes. The application of isoproturon and its metabolites also affects mature earthworms; total protein content and glycogen levels and causes injury and death [65].

3. Ecological Weed Management/Functions

3.1. Principles of Ecological Weed Management

Nature has been playing tricks to maintain the balance between plants and animals and even the species diversity of certain plants and animals since time immemorial. There exists a "pyramid of number" in every ecosystem, balancing the population of one individual against another. The existence of each and every individual, host or pest, is highly essential on Earth, and this preserves biodiversity [66]. It is not advocated to control a pest to near extinction/eradication, which causes considerable damage to ecological balance. Importantly, regulation of the population of individual weeds below the economic threshold is the principal philosophy behind ecological weed management [67]. Therefore, it exercises to limit weed infestation to a density/level at which they will not be highly damaging to crops. Ecological weed management is the amalgamation of different methods that aim to target long-term weed suppression. It targets less direct weed control methods, chemical or non-chemical, and relies on ecological interactions between crops, weeds, and soil for sustainable agro-ecosystem management [68]. Ecological weed management approaches include the development of cultivars resistant to or tolerant of infection, improved crop rotations, cover crops, intercrops, and mulches. Mulching successfully managed a noxious parasitic weed, *Striga* spp., in Sub-Saharan Africa [68]. Ecological weed management fosters agro-ecosystem services (e.g., soil fertility; push–pull strategies against the maize cob borers) [66].

3.2. Preventive Measures rather Than Eradication

Complete eradication of weeds is not admissible because of reduced biodiversity, a lack of herbicide efficacy, and resistant development. Therefore, popularizing integrated weed management is advocated with herbicide use by ensuring safe use to avoid adverse effects on human health, the environment, resistance development in weeds, and the prevention of entry and management of alien invasive weeds. The preventive measures include clean cultivation, the use of clean seeds, keeping the seed bed free from weeds, using well-decomposed organic manures, keeping the bunds and irrigation channels free from weeds, keeping tools and farm machinery clean, and controlling weeds before they attain the reproductive stage [69]. The number of viable weed seeds that remain in the soil reduces to a tune of 25–50% each year, provided the soil is cultivated several times and no more weed seeds are allowed to enter in soil. Preventive methods significantly reduce the amount of weed seeds and vegetative propagules that are stored in the soil [10].

3.3. Weed Surveillance

Weed surveys and monitoring are important in agricultural fields because of the early detection of invasive weeds. This "Weed Surveillance Plan" promotes the early detection of invasive weeds that are new to a geographic area or of very limited distribution [70]. It is an approach towards ecological weed management to know what weed species and communities occur and where in their field to make appropriate and effective weed management decisions for the current growing season and for future crop production. It is most useful because it provides a complete, accurate, and unbiased assessment of the weed populations for a given region [70]. The weed surveillance system encompasses the monitoring of new invasive weed infestations at a very early stage, when an effective control measure is possible. It minimizes the larger weed infestation and curtails the herbicide used for managing weeds. In addition, weed surveillance facilitates weed control with minimal cost and impact on the environment by conserving biodiversity [71]. Surveillance considers the lists of problematic weed species across regions and also inspects the introduction of unexpected species [2]. Many aliens and introduced weeds pose the gravest threat to the environment and economy across the globe [66]. Proper surveillance plans and methods are inevitable for weed risk assessment and to minimize their potential risk [72]. For instance, early detection could effectively control the new invasive alien weed climbing dock (*Rumex sagittatus*) at Maud Island in the Marlborough Sounds. It resulted in successful eradication with the minimum impact on biodiversity [71]. An unmanned aerial system (UAS) equipped with a navigation subsystem, a control subsystem, an image acquisition subsystem, a spray mechanism, a ground station, and a communication subsystem can be used as a cost-effective tool for the surveillance and management of weeds [72].

3.4. Economic Threshold of Weeds

The economic threshold strategy was introduced with the advent of methods that allowed weed control with less labor/work, reliably, and at a relatively low cost [67]. The economic threshold is based on the principle that ca ontrol measure is only worth implementing if its cost does not exceed the monetary value of yield reduction, which is likely to occur in its absence [67]. A crop-specific threshold is used as an aid to decision making. The density per unit area and relative leaf area [67] of an individual weed is usually taken into consideration when working out its economic threshold in a certain crop. One successful approach to the implementation of thresholds has been through the development of computerized decision-aid software [67]. These programs allow users to compare the economic and environmental consequences of potential control actions before committing to a particular decision. However, establishing an economic threshold based on the composite weed population in the fields is very difficult. This economic threshold takes several production factors into account and would be more economical than what was determined based on yield losses alone [73].

3.5. Weed Seedbank Depletion

Understanding the ecological and evolutionary processes underlying the establishment and proliferation of weed species within diversified crop systems is crucial for developing sustainable weed management strategies [15]. Weed seed recruitment forms the foundation for the development of seed banks within both soil and agro-ecosystems. Key aspects of weed biology, such as seed germination, periodicity, dormancy, dispersal, viability/longevity, and the assessment of weed seedbanks, play pivotal roles in ecological weed management [11]. The weed seedbank represents a reservoir of viable seeds found within and on the soil, as well as in irrigation and drainage channels, water reservoirs, compost, and other locations. It significantly contributes to the weed-related challenges in a given area. This soil-based seedbank includes both newly shed seeds from weed plants (known as seed rain) and older seeds that have persisted in the soil for several years.

Sonoskie et al. [15] highlighted that higher soil weed seed densities are associated with larger above-ground weed populations in crops, especially when not adequately controlled. Therefore, it is imperative to assess both above-ground and below-ground weed densities and community composition when designing sustainable weed management strategies, aiming to promote soil biodiversity and ecosystem sustainability. While many buried seeds may perish within a few years, the seeds of certain species can remain viable for decades. It is estimated that only 1–9% of viable seeds produced in a given year will develop into seedlings, with the remainder maintaining their viability and potentially germinating in subsequent years, depending on factors such as burial depth [74]. Tillage practices influence seed survival in several ways. First, the act of tillage itself can stimulate seed germination, such as by exposing seeds to bursts of light or scarifying them. If germination occurs at a depth that prevents emergence or during conditions unsuitable for establishment, the germinated seeds may not survive. Second, changes in soil conditions resulting from tillage can also stimulate germination under conditions unsuitable for establishment. Lastly, the impact of seed predators, pathogens, and physical damage tends to decrease with increasing soil depth [75].

3.6. Competitive Crops

Weeds form a cover over the soil surface in crop fields as well as in non-cropped fallow and wastelands. They have a number of species-wise populations occurring together or separately in a place or places nearer or distantly apart from each other. The association of weeds and crops is determined largely by the degree of competition between them. The spectrum of weed flora is dynamic across crops [66]. Moreover, among the annuals, certain weeds come up very early in the season and others very late. Certain weeds wither away well ahead of crop harvest, while others are seen growing even after crop harvest. Normally, weeds compete with crop plants more severely in the early growth stages; therefore, crop planning should be performed in such a way that it may boost the early growth and vigor of crop plants, which results in better crop competition with weeds. To reduce the adverse effect of weeds in field crops, select long-duration varieties, as these varieties grow quickly and produce canopy early, resulting in shading and thus suppressing the growth of weeds. Significant reductions were observed in the growth (density, dry weight, and height) of *Phalaris minor*, *Chenopodium album*, and *Melilotus indica* in association with the tall wheat genotype ("C 306") compared to the 3-gene dwarf variety ("WL 1562") [13]. A better competitive ability of "WH 291" and "HD 2285" than "HD 2009" and "S 308" against wild oat under late-sown conditions was reported [13]. The semi-dwarf variety of wheat, Kundan (HD 2285) performed better than "C 306", a tall variety, under sub-optimal levels of irrigation and nitrogen and had an equal competitive ability to suppress weeds as that of "C 306". The "Radhey" variety of chickpea is able to reduce weed dry matter as compared to "Pant G 114", "Avrodhi". "HD 2687" and "PBW 343" significantly reduced the density of *P. minor* compared to "WH 157" and "WH 542", and weed control efficiency was also recorded at 74.9% and 71.4%, respectively. Cowpea has a higher weed-smothering capability. Barley is the most competitive, followed by rye, wheat, cultivated oat, and flax.

3.7. Weeds Predation

The weed seedbank is under continuous dynamism due to losses and input/replenishment of seed reservoirs through various means [75]. The potential ways through which weed seeds may be lost from soil are: (i) Predation (eaten up by rats/rodents, insects, and birds); (ii) microbial decay; (iii) aging and senescence; and (iv) germination and emergence from soil (periodicity of germination) [76]. Predation can affect both the accumulation of seeds through seed rain and the removal of seeds from weed seedbanks in soil. The potential predators are rats/rodents, insects, and birds, and they are mainly granivores. Herbivory/grazing by animals may also influence the seed rain considerably. It can decrease weed growth and seed production, stimulate compensatory regrowth, or, in severe cases, cause plant mortality [76].

3.8. Allelopathy

The phenomenon of allelopathy, where either weeds affect crops or crops affect weeds, can lead to direct negative interactions between them [12]. However, it is important to note that while a crop may possess allelopathic properties towards weeds, this effect may not be uniformly inhibitory across all weed species in a field. Instead, when weeds exhibit allelopathy towards a crop, it can significantly impact the crop because only one species (the crop plant) is affected by their influence or targeted [77]. Allelopathic interactions often manifest through root exudates of certain crop varieties or through residues of crops such as maize, sorghum, wheat, barley, or rye, which can inhibit the growth of specific weed species [12]. Effectively utilizing these crop residues as mulch can be highly beneficial for weed control. Using crop residue mulch with allelopathic effects can serve as a self-sustaining weed management strategy, both for concurrent and rotational crops. This approach holds promise for the future of global weed management practices, offering opportunities to develop new crop varieties with allelopathic potential to naturally control weeds, with breeders playing a key role in its success.

Another important aspect is the development of novel bio-pesticides/herbicides derived from plant allelochemicals [78]. The use of non-harmful plants to outcompete harmful ones, as demonstrated in the replacement of parthenium (*Parthenium hysterophorus* L.) in Bangalore, Karnataka, India, represents a novel approach [79]. Numerous ruderal flora and weeds, such as *Cassia sericea*, *Tagetes minuta*, *Mirabilis jalapa*, *Tephrosia purpurea*, *Cassia obtusifolia*, and *Cassia occidentalis*, have been found to exhibit allelopathic effects on parthenium. Among these, *Cassia sericea* has been extensively studied and proven highly effective in replacing parthenium [79]. Furthermore, barley exhibits stronger competitiveness against weeds compared to wheat, primarily due to greater root proliferation in the initial 20–25 days after sowing. Barley also contains allelochemicals, such as gramine. Similarly, sorghum possesses allelochemicals such as hydrocyanic acid (HCN) in its shoots and foliage, making it allelopathic to weed species such as *Abutilon theophrasti*, *Amaranthus hybridus*, *Setaria viridis* and *Bromus pectinatus*. In maize, the primary source of allelochemicals is root exudates, and it exhibits allelopathy towards *C. album* and *Amaranthus retroflexus* [79].

4. System Based Approaches for Non-Chemical Weed Management

4.1. Cropping System Approaches for Ecological Management

Existing literature indicates that incorporating leguminous plants into a cropping system can have positive effects on overall yields and the stability of income compared to monoculture systems [14]. Nevertheless, variations exist among different types of legumes. Short-season legumes, such as groundnuts, are more readily marketable and, therefore, better suited for commercial-oriented agricultural systems [80]. In contrast, long-season legumes such as pigeon pea contribute to enhanced maize yields by increasing phosphorus availability and fixing a substantially larger amount of nitrogen, a critical nutrient in maize-based systems [14]. A triple zero-till (ZT) system incorporating three crops (rice, wheat, and mungbean) with residues, comprising ZT direct-seeded rice with summer mungbean residue (MR)—ZT wheat (ZTW) with rice residue (RR)—ZT summer mungbean (MB) with wheat residue (~MR + ZTDSR − RR + ZTW − WR + ZTMB), demonstrated consistent superiority over the years [80]. This system exhibited approximately 33.5% higher overall productivity (in terms of wheat equivalent yield) than the conventional tillage and rice–wheat system (TPR-CTW). It also resulted in a 25% reduction in nitrogen use (~60 kg N/ha) during rice and wheat cultivation. The conservation agriculture (CA)-based approach holds promise as an alternative to the prevalent conventional tilled approach in the rice–wheat system and serves as a vital strategy for adapting to climate change.

To diversify the predominant rice–wheat cropping system in the Indo-Gangetic Plains, which has encountered numerous challenges, identifying a crop that can serve as a suitable substitute for rice (in terms of profitability) is crucial. The ZT permanent broad bed (~PBB) and flat-bed (ZTFB) practices with residue were consistently superior to conventional tillage in terms of overall system productivity across all three systems. In the cotton–wheat system, the ZTFB and ZT PBB with residue, along with 100% nitrogen application, led to 15% and 13% higher system productivity, respectively, compared to the CT system. This CA-based cotton–wheat system shows promise as a superior alternative to the rice–wheat system and serves as an important adaptation strategy to address climate change. Under the CA-based pigeon pea–wheat system, ZT flat beds with and without residue (ZTFB + R and ZTFB) and permanent broad beds with residue (PBB + R) outperformed conventional tillage practices in terms of system productivity (measured in wheat equivalent yield/WEY). The ZTFB, ZTFB + R, and PBB + R practices resulted in approximately 19%, 18%, and 11% higher system productivity, respectively, compared to conventional tillage. Similar results were observed in the maize–wheat system as well [81]. The addition of legumes in the rice–wheat system, such as rice–wheat–mungbean and rice–wheat–rice–chickpea, reduced the aboveground weed density and weed seedbank density of the rice–wheat system over time. Notably, diversification of the rice–wheat system with the rice–chickpea system reduced

42% *Phalaris minor* (a problematic weed in Indian Indo-Gangetic plains) density compared to rice–wheat [74]. In addition, diversification of maize–wheat rotation with legumes (chickpea and mungbean) could reduce the dominant weeds (above-ground and soil seedbank) while increasing their diversity, resulting in ecological weed management [82]. Long-term adoption of zero-till residue management in post-rainy seasons after puddled rice and cropping intensification with legumes in rice-based systems reduced the weed seed density, above-ground weed flora, and increased crop productivity over time [83].

4.2. Good Agronomic Practices

4.2.1. Soil Solarization

Soil solarization is an environmentally friendly method for soil disinfestation, used to manage soil-borne plant pathogens and control weeds. This technique involves raising soil temperatures to 50–55 °C at a depth of 5 cm and exceeding 40 °C in surface layers, effectively inhibiting seed germination by thermally killing germinating seeds or inducing seed dormancy. Soil solarization has been adopted in over 50 countries, primarily in hot and humid regions. It aligns well with future scenarios in India and can support national food security programs. The process of soil solarization harnesses solar radiation for approximately 4–6 weeks during the summertime, when the soil receives maximum sunlight. The soil absorbs energy from the sun, elevating its temperature to levels lethal to many soil-borne pathogens. This method not only controls pathogens but also enhances soil texture and nutrient availability, which are crucial for plant growth and development.

Studies have demonstrated the effectiveness of solarization in weed control, achieving up to 98% weed elimination in crops such as corn. In contrast, non-solarized control plots have reported up to 90% crop damage due to weeds alone [84]. Globally, solarization has successfully managed annual weeds such as annual bluegrass, *Ageratum* spp., *Amaranthus* spp., barnyard grass, cogongrass, common purslane, *Digitaria* spp., *Portulaca* spp., redroot pigweed, *Setaria* spp., and many others. The elimination of weeds also hinders the growth and spread of pathogenic microorganisms or insects that may complete their life cycles on wild plants. Typically, winter wild plants are more susceptible to elimination, whereas summer wild plants such as *Cyperus* spp. and *Convolvulus arvensis* have shown greater resistance to soil solarization [85].

4.2.2. Stale Seedbed Technique

The stale seedbed technique involves encouraging weed seeds to germinate and then eliminating them through nonselective herbicides or shallow tillage before sowing. This approach proves effective not only in reducing weed emergence throughout the crop season but also in decreasing the overall weed seedbank [86]. Research conducted by Renu et al. [87] has indicated that the stale seedbed technique is particularly efficient when applied under zero-tillage (ZT) conditions. This method is most successful against weed species with seeds primarily located in the topsoil, those with low initial dormancy, and seeds that rely on light for germination. Susceptible weed species for this technique include *Cyperus iria*, *Digitaria ciliaris*, *Eclipta prostrata*, *Leptochloa chinensis*, and *Ludwigia hyssopifolia*.

4.2.3. Crop Establishment Methods

Bed planting has proven to be a superior method compared to traditional flat sowing of wheat, as it led to a 12.5% reduction in the population of *Phalaris minor* when compared to flat sowing [88]. The raised-bed planting of wheat offers several advantages, including the ability to implement mechanical weeding and conserve irrigation water when compared to flooding methods for wheat cultivation. Additionally, bed planting reduces weed infestation by burying weed seeds deep within the soil during bed preparation. Weed seeds located on the top of the bed experience poor germination, as they have limited access to irrigation water. Furthermore, the space between the rows of beds can be utilized for mechanical weed control during the early stages of weed growth. Reshaping the beds before wheat planting can effectively eliminate the initial emergence of *P. minor* seedlings.

4.2.4. Adjusting the Crop Planting Date

By taking into consideration dormancy patterns, it is possible to anticipate the germination seasons of many weeds. With this knowledge, adjustments can be made to crop planting schedules, aiming to either have the crop emerge before the weeds for a competitive edge or to allow weeds to germinate and be managed before or during crop planting. Even a slight advancement in planting dates can offer the crop a notable competitive advantage over weeds. The effectiveness of early crop planting in suppressing weeds is exemplified by the case of *Phalaris minor* in rice–wheat systems in the Indo-Gangetic plains [89]. The adoption of zero-tillage practices enabled wheat crops to be planted 1–2 weeks earlier, enabling the crop to establish itself before the emergence of *P. minor*.

4.2.5. Adjusting the Crop Density

Crop geometry, including row spacing and planting patterns, can significantly impact the competition between crops and weeds. Opting for narrower row spacing can tip the competitive balance in favor of the crop, as it facilitates quicker canopy closure and reduces the availability of light to weeds [90]. For certain cultivars, weed competition can also be lessened by adopting a paired-row planting pattern [91]. For instance, when the rice cultivar "PR 115" was sown in a paired-row pattern (15–30 cm), weed biomass was 25% lower compared to a uniform row spacing of 23 cm. Additionally, using narrow row spacing, such as 15 cm, led to a 16.5% reduction in *Phalaris minor* biomass compared to the standard spacing of 22.5 cm [91]. Furthermore, a higher seed rate of 150 kg ha^{-1} proved effective in reducing populations of *P. minor*, *Oxalis corniculata*, and *Melilotus alba* in contrast to the typical seed rate of 125 kg ha^{-1}.

4.2.6. Fertilizer Management

Generally, weeds exhibit a more aggressive nutrient uptake compared to crops. Therefore, it is desirable to adjust the timing, placement, and source of fertilizers to favor the crop's access to nutrients. In soils with low natural fertility levels, concentrating fertilizers in specific bands can effectively reduce weed biomass in comparison to evenly broadcasting them. Deep banding of fertilizers tends to be more effective than surface banding for this purpose [87]. Placing fertilizer within the crop's root zone can shift the balance of competition in favor of the crop over weeds. For instance, under zero tillage (ZT), seed drills can deposit basal applications of fertilizer beneath the seeds, thereby suppressing weeds, as opposed to traditional farmer practices of broadcasting both seeds and fertilizers. Some nutrient management strategies to reduce early competition from weeds include focusing on phosphate fertilizer placement, implementing basal nitrogen application using materials such as Neem cake or Karanja cake, and postponing urea application by 7–10 days.

4.2.7. Water Management (Irrigation and Drainage)

In irrigated settings, the variation in both spatial and temporal soil moisture conditions presents opportunities for effective weed control and improved weed control efficiency [2]. Planting large-seeded crops in deep soil moisture when the topsoil is dry can provide crops with an initial advantage over weeds [10]. The choice of irrigation method can also influence the distribution and density of weeds. For instance, because wheat can germinate under drier conditions compared to many weeds, sowing under such dry conditions can lead to reduced weed emergence and competition. Surface irrigation, often employing the flooding method, is the predominant irrigation technique used worldwide [87]. The use of flood irrigation and submergence, especially in rice cultivation, results in a different weed community with greater floral diversity compared to upland rice (direct-seeded rice) [86]. The shift to direct seeding has led to changes in the relative abundance of weed species in rice crops. Notably, species such as *Echinochloa* spp., *Ischaemum rugosum*, *Cyperus difformis*, and *Fimbristylis miliacea* have adapted well to the conditions of direct-seeded rice [2]. These species exhibit varying responses in terms of germination and establishment under different post-sowing water regimes, which plays a crucial role in selecting weed constituents for weed communities. Excessive water and fertilizer applications can inadvertently promote weed growth in modern agriculture. Although irrigation systems are typically designed and managed with a specific crop in mind, it is essential to consider the impact of irrigation on weed development as an integral part of modern production systems. Therefore, ensuring appropriate water movement, drainage, and irrigation methods is crucial within the framework of integrated weed management.

4.3. Cover Crops

The integration of cover crops into crop rotations, especially during periods when the land would otherwise remain fallow, stands as an effective approach for weed suppression and the enhancement of soil chemical and physical properties [92]. Cover cropping is commonly employed in conservation agriculture systems and organic farming, where the presence of cover crops is often inversely related to weed biomass. However, even in conventional agriculture, the utilization of cover crops is recommended due to their substantial positive impact on soil fertility, soil erosion reduction, and weed control. Cover crops serve multiple roles, acting as living mulches when interplanted with cash crops, providing dead mulches through their residual plant matter, and offering green manure when they are incorporated into the soil. These multifaceted benefits contribute to weed control by physically suppressing weed emergence, reducing light penetration through high biomass production, and even producing allelopathic compounds that inhibit weed growth. Allelopathic effects are evident in certain cover crops such as buckwheat, oat, cereal rye, and sunflower. The effectiveness of cover crops depends on several factors, including the specific cover crop variety, management practices (e.g., sowing date, incorporation date, agricultural techniques), the composition of the weed community, environmental and soil conditions, the quantity of plant residues, and the rate of decomposition. Cover crops such as hairy vetch (*Vicia villosa*) and cereal rye (*Secale cereale*) can provide consistent and dense ground cover, while crops such as crownvetch (*Coronilla varia*) contribute to long-term soil management [93,94].

4.4. Intercropping

Intercropping offers numerous advantages to a farming system, including enhanced stability, increased yield, and reduced reliance on chemicals such as fertilizers and pesticides. Both research and practical experience from various regions worldwide have consistently shown that intercropping and cover cropping systems tend to be more effective in weed suppression compared to sole cropping systems. This effect is particularly pronounced when utilizing smother crops such as forage legumes, which are interplanted with a main crop such as cereal. Intercropping with grain crops can also be a valuable strategy for weed suppression, especially when the primary crop struggles to compete with weeds [66]. For instance, in an experiment, maize + blackgram (1:1) intercropping demonstrated lower total weed density and weed dry weight compared to other intercropping systems. The combination of maize + blackgram intercropping, along with the application of pendimethalin at 0.75 kg per hectare, applied pre-emergence three days after sowing (DAS) and one-hand weeding 25 DAS, resulted in higher weed control efficiency. Including pulses as an intercrop in jute cultivation was effective in suppressing dicot and sedge weeds by up to 54% [95]. Moreover, intercropping jute with greengram, followed by the application of butachlor and one-hand weeding, achieved an impressive weed control efficiency of 82%, surpassing the 64% achieved through conventional manual weeding.

4.5. Mulching

Mulches serve as effective tools for weed control, employing various mechanisms such as light exclusion, the creation of physical barriers to seed emergence, and allelopathy [68]. Mulch materials encompass a wide range of options, including clean straw, hay, manure, tar paper, sawdust, crop stubbles, and black plastic, among others. Residue mulching plays a vital role in weed suppression by (1) forming a physical barrier that inhibits the emergence of new weeds and (2) releasing allelochemicals into the soil. In a study conducted by Chhokar et al. [96], it was observed that rice residue mulch at a rate of 2.5 tons per hectare was not particularly effective in suppressing weeds. However, when the mulch rate was increased to 5.0 or 7.5 tons per hectare, it resulted in a reduction in weed biomass by 26% to 46% for *Phalaris minor*, 17% to 55% for *Oxalis corniculata*, 22% to 43% for *Medicago sativa*, and 26% to 40% for *Setaria glauca*, in comparison to zero tillage without residue. In the context of zero-till direct-seeded rice, wheat residue mulch at a rate of 5 tons per hectare significantly reduced the emergence of grass, broadleaf, and sedge species by 73% to 76%, 65% to 67%, and 22% to 70%, respectively, compared to a control with no residue [97]. Despite the evident benefits of mulch in weed management, one constraint is the limited availability of crop residues for mulching during the rice season. To address this issue, a practical strategy in rice–wheat systems involves cultivating short-duration catch crops such as mungbean in the fallow period between wheat harvest and rice planting. The entire residue of the mungbean crop is then retained as mulch in the rice fields, effectively contributing to weed management [80]. Materials such as black polyethylene have also found utility in weed control within organic production systems. Black polyethylene serves to elevate soil temperature by allowing the one-way transmission of infrared radiation. In comparison to other mulch materials such as water hyacinth, paddy straw, and wheat straw, black polyethylene has recorded significantly lower weed density and dry biomass in various crops.

4.6. Crop Diversification

Crop diversification serves as a strategic approach for farmers to mitigate the risks associated with crop failure and productivity loss caused by unpredictable weather events. Rotation schemes spanning four years or more have demonstrated a substantial reduction in herbicide usage, benefiting both tilled and untilled farming systems. Rotating crops with dissimilar life cycles or cultural conditions, thereby breaking the weed cycle, stands out as one of the most effective weed control strategies [98]. Other effective rotations include rice–potato–sunflower, rice–mustard–sugarcane, and rice–potato–onion. Inclusion of berseem (*Medicago sativa*) in rice-wheat cropping systems has demonstrated the reduction of *Phalaris minor* seedbanks in a shorter timeframe, as the emerged *Phalaris minor* plants are regularly cut during berseem harvesting, preventing them from setting and shedding seeds in the field [99]. Similarly, in potato-based rotations, the uprooting of germinated *Phalaris minor* occurs during earthing-up or digging operations. In heavy soils, infestations of wild oats that were predominant in maize–wheat systems were entirely eliminated by substituting rice for maize [100]. Effective control of winter annual grasses was achieved during the cultivation of summer annual crops and fallow periods to prevent seed production. Introducing perennial forages such as alfalfa into a rotation has been shown to provide weed control benefits for up to three years, especially in no-till (NT) systems. Both field studies and modeling efforts have revealed that changing management practices can account for a larger percentage of weed control than actual crop changes [74].

4.7. Conservation Agriculture (CA)

4.7.1. Minimum Soil Disturbance/Zero Tillage (ZT)

In conservative tillage systems, such as zero tillage, the process of seed infiltration into the soil occurs relatively slowly through mechanisms such as cracks, the activity of soil fauna, and freeze–dry cycles. This leads to an accumulation of weed seeds, typically ranging from 60% to 90%, in the top 5 cm of the soil. Research has shown that when using moldboard ploughing, most weed seeds are buried in the tillage layer, while chisel ploughing tends to leave a greater proportion of weed seeds closer to the soil surface. Regardless of the tillage method employed, under conditions where moisture is not a limiting factor, the stimulus for germination is generally stronger near the soil surface and diminishes with increasing depth. In situations where weed seeds are positioned directly on untilled soil surfaces, the emerging radicles of these seeds may encounter challenges penetrating the surface of untilled soil, leading to unsuccessful germination [101].

Environments characterized by high disturbance, such as conventional tillage (CT) systems, tend to favor the growth of annual broadleaves, while low disturbance systems such as zero tillage (ZT) are more conducive to perennial weeds and species capable of successful surface germination, such as annual grasses [102]. When compared to tilled soils, ZT systems have shown a higher level of weed species diversity within seedbanks and among emerging weed communities [103]. Reduced emergence of weeds such as littleseed canarygrass in ZT systems may be attributed to factors such as higher soil strength resulting from crust development in the absence of tillage after the rice harvest. This can mechanically impede seedling emergence. Additionally, ZT systems may experience higher levels of weed seed predation. Other potential factors include less fluctuation in soil temperature due to ZT practices, which can moderate soil temperature, as well as lower levels of light exposure, nitrogen mineralization, or gas exchange—factors known to stimulate germination in many weed species following tillage. One notable criticism of CA is its perceived reliance on herbicides compared to tilled systems. However, in Canada, the adoption of no-till (NT) practices has not significantly increased herbicide usage. In the US Great Plains, NT wheat systems have effectively controlled weeds through cultural tactics, reducing herbicide usage by up to 50% compared to conventional tillage (CT) systems. Moreover, in many regions where CA is promoted, herbicides may not be readily available or may be prohibitively expensive, necessitating alternative weed control methods [104].

4.7.2. Permanent Soil Cover/Surface Residue Retention

In CA systems, the common practice is to retain crop residues on the surface rather than resorting to burning or incorporation [90]. Surface residues can influence seed germination through both physical and chemical alterations in the seed environment. Two primary physical effects are notable: A reduction in available light and insulation of the soil surface. This insulation has implications for soil temperature and moisture levels. A reduced light environment tends to have a more significant impact on the germination of small-seeded annual weeds and crops, as they rely more on initial light exposure compared to perennials and larger-seeded species. Surface residues lead to lower daily maximum soil temperatures while having little effect on the daily minimum, resulting in two key changes: Cooler average soil temperatures and reduced temperature fluctuations. Moreover, surface residues alter the chemical environment around weed seeds through allelopathy. The allelopathic effects of stemming from crop residues tend to exert more pronounced effects on smaller seeds. Additionally, surface residues may indirectly encourage seed predation by providing a habitat for foraging and nesting predators. These residues on the soil surface create an insulated boundary between the soil and the atmosphere, reducing evaporative losses and maintaining humidity levels. This heightened microbial activity and biomass under the residues appear to promote higher rates of seed decomposition, ultimately leading to reduced seed persistence [105].

4.8. Physical Weed Management

The surge in organic farming over recent years has spurred significant technological advancements in mechanical tools for weed control. These innovations have been the result of a collaborative effort between agricultural machinery companies and the scientific community. Notable progress has been made in the development of mechanical implements such as torsion weeders, finger weeders, brush weeders, weed blowers, and flex-time harrows, all tailored for intra-row weed management [106]. In agriculture, where crops are more widely spaced, such as sugarcane, cotton, and orchards, specialized machinery such as mini-weeders, power tillers, and mini-tractor-drawn rotavators are employed for effective weed control. For instance, the practice of wider spacing, about 5–6 feet, in sustainable sugarcane initiatives has made mini-tractor-drawn rotavators particularly useful for comprehensive weed control in sugarcane fields. Similarly, the cono-weeder finds its application in wetland weed control, significantly boosting yields in the system of rice intensification. In cotton crops, mini weeders and power tillers play a pivotal role in managing various weed species. These mechanical weed control methods not only contribute to weed management but also enhance productivity while reducing the physical strain on farmers in organic farming systems [66]. Despite these substantial advancements, it is important to note that mechanical methods do have certain limitations. They often entail high initial costs and ongoing expenses related to labor and fuel. Moreover, they may not be as effective in managing intra-row weeds and can be heavily reliant on specific soil and weather conditions, including soil texture and moisture levels, as well as the type and growth stage of the weeds. In the context of herbaceous field crops, the typical approach involves ploughing the soil to a depth of 30–40 cm to invert the soil and bury plant residues. Subsequently, the upper layer of soil is shallow-tilled multiple times using tools such as harrows or rototillers to prepare the field for sowing or planting, thereby removing weeds from the field surface [106].

4.8.1. Weed Control by Hot Water and Hot Foam

Hot water treatment for weed control has undergone extensive research worldwide, yielding favorable outcomes. In the 1990s, the United States pioneered the development of a commercial tool designed to administer hot water for weed management. This approach proves effective against a broad spectrum of annual and numerous perennial weed species. New Zealand also witnessed the successful application of similar devices, where weeds were subjected to prolonged periods of hot water treatment [106]. Notably, hot water treatment is a safe method without any adverse side effects, in contrast to techniques such as flame weeding or radiation. The effectiveness of hot water treatment is particularly pronounced in situations with dense weed populations, as it possesses the capability to thoroughly penetrate the plant canopy. Due to its notable success rate, this technique is now under consideration as a component of precision weed management strategies in Europe. An alternative approach involves the utilization of hot foam instead of hot water, which proves to be more energy efficient [106]. The slow disintegration of foam allows for greater heat transfer to the targeted weed plants. Additionally, the use of steam, as an alternative to hot water, has been reported as a swifter, more efficient, and more sustainable method of weed control, especially in scenarios where weeds are growing on relatively hard surfaces.

4.8.2. Weed Control by Flaming

Flaming has emerged as one of the most widely adopted techniques for thermal weed control, particularly in the realm of organic agriculture [107]. Flame weeding involves the application of intense heat generated by a fuel-burning apparatus, which can be either hand-held or tractor-mounted. Brief exposure to this high heat induces the expansion of intracellular water and disrupts cell membranes, ultimately leading to cellular leakage, dehydration, and cell death [108]. Research has shown that exposure to flame temperatures ranging from 800 to 1000 °C for approximately 1 s can effectively achieve weed control [108]. Importantly, the risk of harm to crop roots is minimal, especially when dealing with heat-tolerant agronomic crops (such as maize, cotton, and sugarcane) or when the flame is carefully directed to the base of the crop to target intra-row weeds.

4.8.3. Weed Control by Abrasive Grit

In a study by Forcella [109], the effectiveness of using grits derived from crop residues, such as corncobs or walnut shells, was demonstrated in the control of small weed seedlings. This was observed in both greenhouse and field experiments. According to reports, employing two on-row applications of air-propelled corncob grit, in conjunction with inter-row cultivation, resulted in a reduction in weed density in corn and an increase in crop yield. When two or three abrasion applications were combined with between-row cultivation throughout the season, in-row weed control consistently exceeded 90%. Furthermore, another study [110] found that the application of air-propelled granulated materials such as walnut shells, maize cobs, greens, and a combination of fertilizers (including pelletized poultry manure) and soybean meal led to a substantial reduction in weed biomass, ranging from 69% to 97%, in tomato and pepper (*Capsicum annuum*) cropping systems when compared to uncontrolled weedy conditions.

4.9. Biological Control

The interest in biological control methods has significantly increased since the 1980s, aligning with the growth of organic farming practices within the framework of sustainable agriculture. Researchers, industrial firms, and stakeholders have globally recognized the importance of biological control. However, despite the growing enthusiasm for biological control tools, the market share of bioherbicides, which are natural products used for weed control, remains relatively small, accounting for less than 10% of all types of biopesticides (including biofungicides, biobactericides, bioinsecticides, and bionematicides). Many of the commercially available bioherbicides are mycoherbicides, such as DeVine, Collego, Smoulder, and Chontrol. For example, the rust fungus *Puccinia canaliculata* (Schw.) Lagerh. shows promise in controlling yellow nutsedge (*C. esculentus*). When this pathogen is released early in the spring onto yellow nutsedge seedlings, it reduces the plant population, tuber formation, and flowering [111].

4.10. Artificial Intelligence and Robotics Application

Weed models have proven invaluable in shedding light on the intricate interplay between weeds, management practices, and environmental factors. These models offer a means of pinpointing the specific areas within a conservation agriculture (CA) system where weed control efforts should be concentrated. Furthermore, the wealth of existing data can be harnessed through meta-analyses to quantify how weeds respond to CA adoption under specific conditions [112]. The future of weed management holds promise with the emergence of robotic systems [112]. These advanced systems will have the capability to collect data on weed presence, store and analyze this information, facilitate decision making regarding the timing and location of weed control efforts, carry out precise weed removal through robotic deployment, and subsequently gather data on treatment effectiveness, allowing for post-treatment evaluation. Robotic weed management encompasses a four-step process: Guidance, identification, precision weed removal, and mapping of weed species [112]. The feasibility and success of robotic weed control systems hinge upon several factors, including accurate machine vision analysis, the efficiency and suitability of the robotic components, variable-rate application technology, the support of a decision-making system, and the robustness of weed-sensing tools [113]. A wide array of inter- and intra-row weed control tools is already available, including inter-row hoes, basket weeders, brush hoes, powered vertical axis tines, finger weeders, spring tine harrows, torsion weeders, mini-ridgers, rotating wire weeders, and pneumatic weeders [114–116].

5. Recommendations or Concepts for Future Research

Non-chemical weed management in large production areas and intensive farming systems is a great challenge. An integrated approach including agronomic, cultural, physical, and mechanical methods is required to achieve sustainable weed [117]. Green revolution-based intensive agriculture led to several secondary and tertiary problems, such as herbicide resistance and pollution of soil and water. Food security is no longer the main aim of agriculture research for development, but nutrition, food safety, and diet diversity are. Herbicide-based weed management seems prudent for monocropping but cannot meet the expectations of consumers who are looking for safe food. Non-chemical weed management utilizing agronomical tools and techniques may help enhance environmental health and food quality. Cropping system-based sustainable agriculture technologies, such as conservation agriculture, are important to reduce the limitations and challenges of weed competition in agriculture. Innovative methods and new approaches, such as cover crops, competitive cultivars, sustainable intensification, and diversification of production systems, can ensure sustainable agriculture. A significant reduction in pesticide use may enhance the food safety, agricultural productivity, and quality of life of growers and consumers in an environmentally friendly way.

6. Conclusions

Herbicide-based weed management has demonstrated its potential as a cost-effective approach to controlling weeds. The widespread adoption of herbicides in agrochemical-based agriculture, particularly in regions where herbicide-tolerant crops have gained popularity, has been notable. However, the responsible use of herbicides is not always adhered to, leading to various challenges, including the development of herbicide resistance and cross-resistance. It has become increasingly evident that relying solely on herbicides as a weed control method is not a sustainable and effective long-term strategy. Furthermore, concerns related to herbicide resistance, environmental pollution, and the growing interest in organic agriculture have compelled scientists to explore innovative, non-chemically integrated solutions. These solutions encompass the use of robust crop varieties, conservation agriculture practices, crop diversification, cover cropping, appropriate nutrient and water management, and integrated weed management approaches. These integrated strategies are aimed at ensuring the safe and sustainable production of essential crops.

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