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Integrated Weed Management in Wheat: Role of Phytoextracts and Biotechnology Approaches

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Integrated Weed Management (IWM) in wheat production is essential for sustainable agriculture, aiming to control weed populations while minimizing environmental impact. Traditional weed control methods, such as herbicide use, often lead to the development of herbicide-resistant weed species. To address this issue, IWM incorporates a range of strategies, including cultural, mechanical, biological, and chemical methods. Among these, the use of phytoextracts (plant-derived

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compounds) and biotechnology approaches has shown great promise in enhancing weed control in wheat fields. Phytoextracts, through mechanisms like allelopathy, inhibition of photosynthesis, and growth regulation, offer a natural alternative to synthetic herbicides by suppressing weed growth and seed germination. Meanwhile, biotechnology approaches, such as the development of herbicide-resistant wheat varieties, molecular breeding for enhanced allelopathy, and the use of microbial biocontrol agents, provide innovative solutions for effective weed management. The synergy between phytoextracts and biotechnological advancements offers a more sustainable, eco-friendly approach to managing weeds in wheat production. This paper discusses the role of phytoextracts and biotechnology in IWM, emphasizing their potential to reduce reliance on chemical herbicides, minimize environmental impact, and promote long-term agricultural sustainability.

Keywords: Phytoextract; RNAi; genetic engineering; herbs; weed management.

1. INTRODUCTION

Weed management in wheat farming is a critical aspect of agricultural productivity. Weeds compete with crops for nutrients, water, and light, leading to significant yield losses if not properly controlled. Integrated weed management (IWM) is an ecological approach that uses a combination of cultural, mechanical, chemical, and biological strategies to control weeds sustainably Ambaye et al., 2021). Among the various strategies, the use of phytoextracts and biotechnology approaches has gained increasing attention in the recent past due to their potential to offer more sustainable, eco-friendly alternatives to chemical herbicides. Invasive crop species disrupt primary crops and pose a challenge in agriculture, with synthetic herbicide use raising ecological and health concerns. Plant-based alternatives, such as allelopathic extracts from sorghum and medicinal shrubs, show potential to combat weeds (Ionata et al., 2024). Species like *Persicarialapathifolia*, *Artemisia argyi*, and *Ferulaassafoetida* have demonstrated weed-inhibiting properties. Research on allelochemicals from plants could offer sustainable solutions, with species like *P. monspeliensis* and common grasses showing promise for natural herbicidal effects in agroecosystems. Plants rich in secondary metabolites such as tannins, terpenoids, alkaloids and flavonoids have antimicrobial properties since their use increasing rapidly for management diseases (Wang et al., 2021). Phytoextracts (plant extracts) or plant derivatives are biological antifungal agents have potential to overcome fungal diseases without human health risks. Synthetic fungicides significantly impact both aquatic and terrestrial ecosystems. Extensive use of copper-based fungicides leads to copper accumulation, which adversely affects soil microorganisms and earthworms. These applications drastically reduce microbial populations, impairing the soil's nutrient-holding capacity and rendering it nearly sterile. Thus, using fungicides to combat soil-borne diseases poses serious environmental and health risks. (Guidi-Nissim et al., 2023).

2. PHYTOEXTRACTS IN WEED MANAGEMENT

Phytoextracts refer to plant-based extracts that can be utilized to control weeds either by inhibiting seed germination, disrupting growth, or affecting metabolic processes in weeds. These extracts are derived from specific plants that have natural herbicidal properties. The use of phytoextracts for weed management is a part of organic and integrated weed management systems (Hoang et al., 2021). Many plants naturally produce chemicals that can suppress the growth of neighboring weeds. These allelopathic chemicals can be extracted and applied to wheat fields to reduce weed germination or growth. Phytoextracts may contain compounds that inhibit weed growth directly. For example, compounds like phenolics, alkaloids, and terpenes can have herbicidal effects. Unlike chemical herbicides, phytoextracts are biodegradable and typically do not have long-term negative impacts on the environment (Zheng et al., 2024). They can be used to reduce reliance on synthetic herbicides, minimizing harmful residues on crops and in soil. Certain phytoextracts can be selectively effective against specific weed species without harming the wheat crop (Wang et al., 2021). Compounds like alkaloids and phenolic acids present in phytoextracts can disrupt the cell membrane integrity of weeds, leading to leakage of cell contents, dehydration, and ultimately, plant death. Some phytoextracts contain compounds that inhibit photosynthetic enzymes or processes in weeds, reducing their ability to produce food and survive. For example, *Tobacco* extract contains compounds that interfere with photosynthesis in certain weeds. Some phytoextracts contain plant hormones or analogs that affect the growth regulators of weeds. For instance, extracts from plants like *lemon grass* (Cymbopogon citratus) can affect the auxin-regulated processes in weeds, disrupting their growth (Xu et al., 2023).

3. PREPARATION OF PLANT EXTRACTS

Plant sample that may be root, stem, leaf, flower, fruit, bark taken as fresh and dried sample for extraction. Dried sample preferred over fresh sample because of their stability on the other hand fresh sample decay faster than dried sample. Moreover, smaller size particles of sample in powdered form have greater surface contact to solvent for efficient extraction than grinded sample (Bhat et al., 2022). Extraction means separation of soluble plant metabolites by using suitable solvents. Maceration, Decoction and infusions are conventional methods used for extraction. Choice of solvent depends upon the type of compound to be extracted. Water used as solvent for extraction of phenolic acids, alkaloids, flavonoids, lectins, glycosides and phenylpropanoids contents (Riaz et al., 2022). Tannins, polyphenols, flavanol, terpenoids and alkaloids extracted in Ethanol. On the other way saponins, tannins, polyphenols, terpenoids, flavones and anthocyanin extracts obtained by Methanol solvent. Acetone used to extract alkaloids, sugars, tannins and quinones from plant material. Chloroform could also be used for extraction of the bioactive compounds like anthocyanin, flavonoids, flavones and polyphenols. Other than conventional methods there are some modern techniques like ultrasonic assisted extraction and microwave assisted extraction are also used for preparation of phytoextracts (Dhaliwal et al., 2020).

4. EXAMPLES OF PHYTOEXTRACTS USED IN WEED MANAGEMENT

Eucalyptus extracts contain compounds like eucalyptol, which can inhibit seed germination and growth of various weeds. Black Walnut also known as Juglans nigra produces juglone, an allelopathic compound that can suppress weed growth (Alsafran et al., 2022). Allelopathic Plants like rye (Secale cereale) and clover have been studied for their potential to produce phytoextracts with herbicidal properties. Allelopathic compounds from sorghum have shown phytotoxic effects against various weeds in field crops (Li et al., 2022). Water extracts of *Artemisia argyi* have been effective in inhibiting weeds like *Brassica pekinensis*, *Lactuca sativa*, *Portulaca oleracea*, *Oxalis corniculata*, and *Setariaviridis*. Persicarialapathifolia Extract has shown potential in suppressing *Echinochloacolona* weed growth (Anerao et al., 2022). Ferulaassafoetida Extract at concentrations of 0.75%, it reduces the germination of *Amaranthus retroflexus* weed seeds by approximately 70%. Ricinus communis also known as Castor Bean Extract used in concentrations of 1%, it inhibits the germination of various weed species, including *Amaranthus retroflexus*(Maurya et al., 2023).

5. BIOTECHNOLOGY APPROACHES IN WEED MANAGEMENT

Biotechnology offers innovative approaches to weed management, focusing on genetic engineering and molecular tools to develop crops with enhanced resistance to weeds or alternative methods for weed control (Hafshajani et al., 2022). Biotechnology is revolutionizing various aspects of agriculture, and weed management is no exception. The development of genetically modified (GM) crops, along with other biotechnological tools, is a key aspect of integrated weed management in wheat (Cavelius et al., 2023). Genetic engineering of wheat for weed resistance involves modifying the wheat plant’s genetic makeup to make it more tolerant to herbicides, or even able to outcompete or suppress weeds. This is an important area of research because herbicide resistance is a significant problem in agriculture, and the management of weeds in wheat crops is crucial for improving yields (Vera et al., 2021).

5.1 Genetic Engineering of wheat for Weed Resistance

One of the most explored biotechnology approaches is the development of herbicide-tolerant wheat (Rheay et al., 2021). Genetically modified wheat could be engineered to tolerate specific herbicides, allowing farmers to apply herbicides selectively to kill weeds while keeping the wheat crops unharmed. Genetically modifying wheat to express traits such as herbicide resistance (e.g., glyphosate resistance) can be an effective solution for weed management in areas where weeds have developed resistance to commonly used herbicides (Takase et al., 2021). Some genetically modified wheat plants are being developed to express a glyphosate-tolerant enzyme, such as CP4 EPSPS, which allows wheat to survive glyphosate application while weeds are controlled. This would provide a non-chemical means of controlling weeds without harming the crop. Other traits are being developed to make wheat more tolerant to herbicides like glufosinateor dicamba, which target different enzymes in plants (Cristaldi et al., 2020).

Fig. 1. Various strategies for integrated weed management

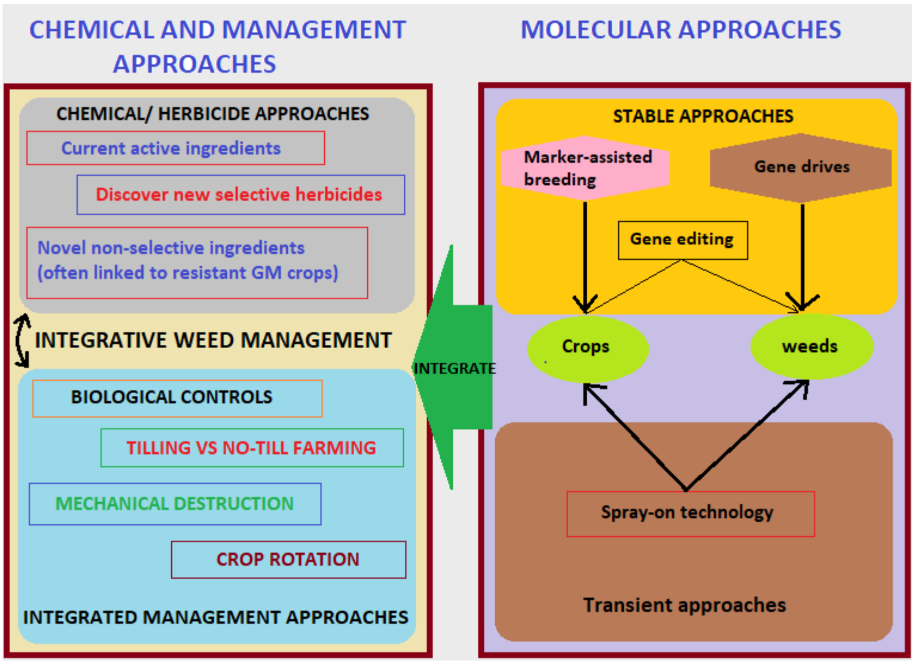

Fig. 2. Difference between traditional and molecular approaches of IWM

Tolerance to these herbicides would make weed management more flexible for wheat farmers. Another approach to managing weed resistance is to engineer wheat plants that can break down herbicides in the soil. This would reduce the impact of herbicide residues, preventing harm to subsequent crops and reducing the risk of herbicide resistance in weeds. As of now, wheat genetic engineering is still under research and development (Learning et al., 2022). While herbicide-tolerant wheat has been created in labs, there are limited commercial releases of genetically engineered wheat, mainly due to regulatory and consumer acceptance issues. However, the development of herbicide-tolerant and weed-resistant wheat could become more common in the future, especially if the push for sustainable agriculture and reducing herbicide use intensifies (Ibrahimpašić et al., 2021).

5.2 Genetic Engineering for Allelopathy

Allelopathy refers to the natural ability of some plants to release chemicals that inhibit the growth of surrounding plants, particularly weeds. Genetic engineering can be used to enhance this property in wheat plants. By increasing the production of certain chemicals in wheat, it may help suppress weed growth around the wheat plants, reducing the need for herbicide use (De-bari et al., 2020). Another biotechnology approach is to use genetic modification to enhance a wheat crop’s natural allelopathic properties. This would allow the wheat plant to produce more powerful natural chemicals that can suppress weed growth, offering a natural and targeted approach to weed control. Biotechnological tools, including molecular breeding and gene editing techniques like CRISPR-Cas9, can be used to enhance the allelopathic properties of wheat (Rahman et al., 2022). By identifying and incorporating genes responsible for the production of allelopathic compounds, scientists could develop wheat varieties with built-in weed suppression properties. These varieties could naturally release chemicals that suppress weed growth, reducing the need for chemical herbicides and promoting a more sustainable farming system. The first step in genetic engineering for allelopathy is identifying the specific allelochemicals that effectively inhibit weed growth (Ewunie et al., 2021). These compounds can include phenolic acids (like ferulic acid), flavonoids, and glucosinolates, which are produced by many plants. Once the genes responsible for producing these allelochemicals are identified, they can be cloned and inserted into crop plants. For example, inserting genes from allelopathic plants into a non-allelopathic crop could endow the crop with the ability to produce these inhibitory chemicals. In some cases, researchers may modify the crop’s biosynthetic pathways to increase the production of certain allelochemicals (Tripathi et al., 2021). This might involve upregulating genes in the plant’s metabolism that lead to higher production of allelopathic compounds. Genetic engineering can be used to create transgenic crops that either produce new allelopathic compounds or have enhanced production of existing compounds. This could allow crops like wheat, rice, or maize to release more allelopathic chemicals from their roots or leaves, suppressing weed growth in the surrounding area (Balyan et al., 2024).

5.3 RNA Interference (RNAi) Technology

RNA interference (RNAi) involves the silencing or downregulation of specific genes by introducing small RNA molecules (such assiRNAormiRNA**)** into the organism. These small RNA molecules can degrade mRNA molecules or prevent their translation into proteins, effectively silencing the targeted gene (Basak et al., 2021). In agricultural biotechnology, RNAi has been used to regulate gene expression in pests, plants, and microbes. By targeting essential genes in weeds, RNAi technology can either disrupt their growth, reproductive processes, or stress responses, making them easier to control or eradicate (Basak et al., 2020). This technology can potentially create "weed-resistant" crops or crops with the ability to interfere with the growth and germination of nearby weeds. By silencing genes involved in seed germination or early development, RNAi can prevent the weed from establishing itself. This could be useful in pre- or post-emergence applications. Weeds require cell division for growth and survival. RNAi can target genes that regulate cell division (such as those involved in the mitotic cell cycle), halting the development of weeds (Jabborova et al., 2021). By silencing genes responsible for flowering or fertility, RNAi can reduce the weed’s ability to reproduce, preventing the spread of the weed population. Inducing male sterility via RNAi can render weeds incapable of reproducing sexually, further reducing their spread. RNAi can be employed to target specific genes that are essential for the growth or survival of a particular weed species. This means that only the weed will be affected, leaving surrounding crops and plants unharmed (Jadhav et al., 2020). RNAi technology holds promise for improving environmental safety compared to chemical herbicides. Since RNAi molecules are short-lived and degrade quickly in the environment, there is less concern for long-term environmental contamination or bioaccumulation (Kundu et al., 2023).

5.4 Microbial Biocontrol Agents

Biological control through the use of beneficial microorganisms, such as fungi, bacteria, and nematodes, is another promising biotechnology approach. Certain microbial agents can target weed seeds or seedlings, either through competition for resources or by producing compounds that inhibit weed growth (Liao et al., 2021). For example, specific soil-borne fungi or bacteria could be used to control invasive weed species in wheat fields. Fusarium species are soil-borne fungi known to infect and kill certain weed species. Some strains of *Fusarium* can parasitize weed roots and stems, causing them to rot or be stunted. These fungi have been used to target weeds like *Canada thistle* (*Cirsium arvense*) and *knotweed* (*Polygonum spp.*). Colletotrichum spp. are known for their ability to infect a range of plants, including weeds (Malabadi et al., 2023). For example, *Colletotrichum gloeosporioides* has been used to control weeds like *Parthenium* (*Parthenium hysterophorus*) by causing anthracnose disease, which weakens and kills the weed. Alternaria spp. have been shown to cause severe damage to weed species like *bindweed* (*Convolvulus arvensis*), and *ragweed* (*Ambrosia spp.*), effectively reducing their growth and seed production (Meena et al., 2020). Bacteria from the *Pseudomonas* genus are capable of producing plant-growth-inhibiting chemicals. For example, *Pseudomonas fluorescens* has been investigated for its ability to suppress weed germination and growth by competing for nutrients and producing allelopathic substances. Some strains of *Bacillus* bacteria, such as *Bacillus thuringiensis*, produce insecticidal toxins, but they have also shown potential as biocontrol agents for weeds (Nigam et al., 2021). For instance, *Bacillus subtilis* can suppress the germination of weeds like *black nightshade* (*Solanum nigrum*) by producing substances that interfere with weed seedling establishment. Cucurbit yellow stunting disorder virus (CYSDV)has shown potential in controlling weed species such as *cucurbit* weeds (e.g., *melon* and *squash*), as it reduces the vigor and reproduction of these plants. To enhance the stability, viability, and ease of application of microbial agents, researchers are working on creating more robust formulations that can be easily applied in the field (Ozyigit et al., 2023).

6. INTEGRATED WEED MANAGEMENT (IWM) WITH BIOTECHNOLOGY

Biotechnology is increasingly being integrated intoIntegrated Weed Managementsystems. IWM combines multiple strategies, such as herbicide application, mechanical control, crop rotation, and biological control, to manage weeds sustainably (Pinto et al., 2023). The aim is to use biotechnology as one component of a larger, holistic weed control approach. Herbicide-tolerant crops are being incorporated into IWM strategies, rotating with non-GM crops or using cover crops that naturally suppress weed growth. This reduces reliance on herbicides and helps mitigate the development of herbicide-resistant weed populations (Prakash et al., 2022). Microbial agents and genetic modifications can be combined with chemical herbicides to reduce herbicide use and control herbicide-resistant weeds. For example, genetically modified crops could help reduce weed competition while maintaining overall crop health and yield. Precision agriculture involves using technology to optimize agricultural practices by collecting and analyzing data to make informed decisions (Singh et al., 2021). In weed management, precision agriculture tools, like GPS, drones, and remote sensing, are increasingly being combined with biotechnology to create targeted, data-driven weed control solutions. Drones equipped with imaging technology can identify and map weed populations in real-time. This data can be used to apply targeted interventions, such as gene editing or microbial treatments, to specific areas of a field, reducing the overall use of herbicides. Biotechnology and precision agriculture can enable more targeted herbicide use by identifying weed species and applying herbicides only where necessary, minimizing chemical use and reducing environmental impact (Singh et al., 2021).

7. COMBINATION OF PHYTOEXTRACTS AND BIOTECHNOLOGY APPROACHES

An integrated approach that combines phytoextracts and biotechnology can enhance weed management strategies in wheat farming. The use of biotechnology to develop wheat varieties with increased allelopathic potential or resistance to herbicides can be paired with the application of natural herbicides from phytoextracts to create a more sustainable, multi-layered defense against weeds (Singh et al., 2022). Combining these two approaches may help reduce reliance on synthetic chemicals, leading to more sustainable farming practices. Phytoextracts can complement biotechnology approaches, leading to broader control over a range of weed species with different growth patterns and resistance profiles (Sreenikethanam et al., 2022). The strategic use of phytoextracts alongside herbicide-tolerant wheat crops can reduce the development of herbicide-resistant weeds. Phytoextracts can be used in conjunction with herbicide-resistant wheat varieties to manage weeds more effectively. For example, phytoextracts could be applied alongside herbicides to reduce the overall herbicide load while still maintaining effective weed control (Sundarrajan et al., 2024). Biotechnology could also be used to enhance the efficacy of phytoextracts. For example, genetic modifications could be made to enhance the production of specific allelopathic compounds in wheat, making them more potent in suppressing weed growth. Combining phytoextracts and biotechnology could lead to a more sustainable farming system that reduces dependence on synthetic herbicides, conserves biodiversity, and promotes soil health (Tavali et al., 2022).

8. CHALLENGES AND FUTURE DIRECTIONS

While the combination of phytoextracts and biotechnology approaches shows promise, there are several challenges: Genetically modified crops often face regulatory hurdles, delaying their approval for use in many countries. Producing phytoextracts in large quantities for widespread agricultural use can be difficult and expensive (Thakur et al., 2021). The diversity and complexity of these phytochemicals make it difficult to pinpoint specific compounds that can be harnessed for effective weed management. One of the primary concerns with biotechnology is the potential for gene flowfrom genetically modified (GM) crops to wild relatives or non-GM crops. If genes engineered to enhance weed resistance or crop protection are inadvertently transferred, it could lead to unintended ecological consequences (Tripathi et al., 2020). Phytochemicals often vary in their concentration and effectiveness based on environmental factors such as soil type, climate, and plant health. Biotech-based solutions, including genetically engineered crops or biocontrol agents, face significant regulatory scrutiny and public concern. While biotechnology and phytoextracts offer more sustainable alternatives to herbicides, their long-term environmental impact still requires careful evaluation (Yang et al., 2022). However, the continued research into plant biology, genetics, and sustainable agriculture holds great promise for further developing these methods, making them more effective and widespread in the future (Zang et al., 2023).

9. CONCLUSION

Weed management through phytochemistry and biotechnology offers tremendous promise, but it faces several challenges that need to be addressed. The complexity of plant chemicals, environmental variability, regulatory hurdles, and the potential ecological risks of biotechnology require careful consideration. However, advances in both areas such as the discovery of new phytochemicals, the use of gene editing, and the development of effective microbial biocontrol agents provide hope for sustainable, eco-friendly alternatives to traditional weed control methods. Integrating these approaches into an effective integrated weed management system will be key to future success, contributing to more sustainable agricultural practices and reduced reliance on chemical herbicides.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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