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Advances in herbicide-resistant weed management in soybean production systems

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Abstract

Herbicide resistance among weed populations poses a critical challenge for soybean production systems worldwide. This article explores the emergence, evolution, and current state of herbicide-resistant weeds in soybean cultivation, focusing on strategies to mitigate resistance, including chemical, mechanical, and integrated weed management approaches. Comprehensive data and case studies illustrate the efficacy of various management practices, offering insights into sustainable soybean production in the face of rising resistance issues.

Keywords: Herbicide resistance, weed populations, soybean production, herbicide-resistant weeds

Introduction

Weed management is a critical component of modern agriculture, directly influencing crop productivity, quality, and overall sustainability. Weeds compete with crops for essential resources such as light, water, nutrients, and space, leading to significant yield losses if left unchecked. In soybean (*Glycine max* L.) cultivation, effective weed control is particularly vital due to the crop's high economic and nutritional value. However, the over-reliance on chemical herbicides as the primary weed control strategy has resulted in the widespread emergence of herbicide-resistant weed populations, posing a severe threat to agricultural systems worldwide. Herbicide resistance has evolved rapidly over the past few decades, driven by the repeated application of herbicides with the same mode of action. Weeds such as *Amaranthus palmeri* (Palmer amaranth), *Conyza canadensis* (Horseweed), and *Lolium rigidum* (Annual ryegrass) have developed resistance to multiple herbicide classes, including glyphosate, ALS inhibitors, and PPO inhibitors. These resistant populations not only reduce the efficacy of chemical controls but also increase production costs and necessitate higher herbicide application rates, raising environmental and health concerns.

The challenges posed by herbicide resistance have prompted a growing interest in sustainable and diversified weed management approaches. Non-chemical methods, including mechanical, cultural, and biological practices, have emerged as promising alternatives or complements to herbicides. These methods leverage ecological principles and resource management strategies to suppress weed populations while preserving environmental integrity. When integrated into a comprehensive weed management framework, these approaches, collectively known as Integrated Weed Management (IWM), offer a holistic solution to the problem of resistance while ensuring long-term agricultural sustainability.

Objective

The objective of this paper is to explore sustainable weed management strategies, focusing on non-chemical and integrated approaches to address herbicide resistance and enhance agricultural productivity and environmental sustainability.

Evolution of Herbicide Resistance in Weeds

Herbicide resistance in weeds has emerged as a significant challenge in modern agriculture, driven by the extensive and often repetitive use of herbicides over the past several decades.

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The phenomenon occurs when weed populations develop the ability to survive applications of herbicides that were previously effective, thereby reducing the efficiency of weed management strategies and threatening crop productivity. The evolution of herbicide resistance is a classic example of adaptive evolution, where selection pressure imposed by herbicide application favors individuals with resistance traits. Research has shown that resistance can result from several mechanisms, including target-site mutations, enhanced metabolic detoxification, reduced herbicide absorption, or sequestration. Among these, target-site resistance is the most well-studied, involving alterations in the herbicide's binding site, rendering it ineffective. For example, resistance to acetolactate synthase (ALS) inhibitors and glyphosate has been frequently linked to mutations in genes encoding the enzymes targeted by these herbicides. Historical studies reveal that resistance evolution is accelerated by the repeated use of herbicides with the same mode of action. This pattern has been observed worldwide, particularly with glyphosate, which became a cornerstone of weed control after the introduction of glyphosate-resistant (Roundup Ready) crops. By the early 2000s, several weed species, including *Amaranthus palmeri* (*Palmer amaranth*) and *Conyza canadensis* (horseweed), had developed resistance to glyphosate, complicating weed control in major cropping systems such as soybean, maize, and cotton. The role of non-target-site resistance, where weeds metabolize or sequester herbicides before they can reach their target sites, has also gained attention. Studies on resistant populations of *Lolium rigidum* (Annual ryegrass) in Australia and *Echinochloa colona* (jungle rice) in Asia highlight the complexity of resistance mechanisms and the ability of weeds to develop cross-resistance to multiple herbicides with different modes of action.

Ecological factors play a pivotal role in resistance evolution. Monoculture systems and the lack of crop rotation reduce biodiversity and encourage the proliferation of resistant biotypes. The persistence of weed seeds in the soil seed bank, coupled with their ability to disperse through wind, water, or human activity, further exacerbates resistance challenges. A study on *Alopecurus myosuroides* (Blackgrass) in Europe revealed that highly intensive agricultural systems with limited herbicide diversity have significantly higher incidences of resistance. The economic implications of herbicide resistance are profound, leading to increased production costs due to the need for alternative management strategies, such as more frequent herbicide applications, integration of mechanical control methods, or the adoption of herbicide-resistant crop technologies. These changes can strain both farmers and the agricultural supply chain, emphasizing the urgent need for sustainable solutions. In recent years, research has focused on understanding the genetic basis of resistance and the evolutionary dynamics of resistant populations. Advances in molecular biology and genomics have enabled the identification of resistance-conferring genes and their inheritance patterns, offering potential avenues for developing new herbicides or resistance management tools. Studies leveraging next-generation sequencing have uncovered previously unknown resistance pathways, further highlighting the adaptability of weed species under selective pressure. The evolution of herbicide resistance underscores the importance of adopting integrated weed management (IWM) approaches. While chemical herbicides remain a critical component of weed control, reliance on them as a singular strategy has proven unsustainable. The integration of cultural practices, such as crop rotation, cover cropping, and optimizing planting densities, can reduce weed pressure and

mitigate the evolution of resistance. Educational programs and policies promoting herbicide stewardship and resistance monitoring are equally essential to address the issue comprehensively. Herbicide resistance in weeds is a dynamic and multifaceted problem that reflects the interaction of biological, ecological, and agricultural factors. The insights gained from previous studies highlight the need for holistic, science-driven strategies to manage resistance effectively. By combining traditional and innovative methods, the agricultural community can safeguard the efficacy of herbicides and ensure sustainable food production systems.

Chemical Weed Management Strategies

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Chemical weed management remains a cornerstone of modern agriculture, particularly in large-scale cropping systems where manual and mechanical methods are less feasible. The use of herbicides provides a cost-effective and efficient means to control weeds, reduce competition, and optimize crop yield. However, the rising incidence of herbicide-resistant weed populations necessitates the adoption of refined chemical weed management strategies to ensure sustainable agricultural practices.

1. Herbicide Selection and Rotation

An essential strategy for effective chemical weed management is the judicious selection of herbicides with varying modes of action. Rotating herbicides reduces the selection pressure on weed populations, thereby delaying the onset of resistance. For instance, alternating herbicides that target different metabolic pathways—such as acetolactate synthase (ALS) inhibitors, photosystem II inhibitors, and synthetic auxins—has proven to be effective in managing diverse weed populations.

Research has demonstrated that weed resistance to specific herbicides, such as glyphosate, is often driven by the repeated use of a single mode of action. Diversifying herbicides within a cropping season or across seasons has been shown to maintain long-term efficacy. For example, studies in maize and soybean systems in the United States have revealed that integrating pre-emergence herbicides with post-emergence applications significantly improves weed control.

2. Pre-Emergence and Post-Emergence Herbicides

Herbicides can be categorized based on their application timing relative to crop and weed emergence: pre-emergence and post-emergence.

- **Pre-Emergence Herbicides:** These are applied to the soil before the weeds germinate and establish. They form a chemical barrier that prevents weed seedling emergence by inhibiting key physiological processes such as cell division or root development. Herbicides like pendimethalin, atrazine, and metribuzin are commonly used as pre-emergence treatments in crops like soybeans and cereals.
- **Post-Emergence Herbicides:** Applied after weeds have emerged, these herbicides target actively growing weeds. Glyphosate and glufosinate are widely used non-selective post-emergence herbicides, while selective herbicides like dicamba and fomesafen control specific weed species without harming the crop.

Integrating pre- and post-emergence herbicides within a season maximizes weed control and mitigates resistance development, as shown in studies from Canada and Australia.

3. Herbicide Mixtures and Tank-Mixing

Combining herbicides with different modes of action in a single application (Tank-mixing) or through sequential applications can enhance weed control while reducing the risk of resistance. Mixtures provide multiple mechanisms of action against weeds, targeting various physiological pathways and reducing the likelihood that a weed population will develop resistance to all components.

For example, a mixture of atrazine (A photosystem II inhibitor) and mesotrione (A pigment synthesis inhibitor) has been found highly effective against glyphosate-resistant *Amaranthus palmeri* in soybean fields. Studies suggest that mixtures can also help control weed species that have evolved resistance to a single mode of action.

4. Precision Application Technology

Recent advancements in agricultural technology have facilitated more precise herbicide application, reducing waste and minimizing environmental impact. Technologies such as GPS-guided sprayers and site-specific weed management systems allow farmers to target weeds more accurately, applying herbicides only where needed. Studies from Europe and the United States highlight the role of precision agriculture in improving the efficiency and sustainability of chemical weed control.

5. Residual Herbicides for Long-Term Control

Residual herbicides remain active in the soil for extended periods, providing long-term control of weed seedlings. These herbicides, such as isoxaflutole and pyroxasulfone, are particularly effective in preventing secondary flushes of weeds after the initial application. Research has shown that the use of residual herbicides in no-till systems significantly reduces weed seed bank densities over time.

6. Addressing Herbicide Resistance

Managing herbicide-resistant weeds is a critical aspect of chemical weed management strategies. Strategies to address resistance include:

- **Target-Site Resistance Management:** Rotating herbicides with different target sites prevents the selection of resistant biotypes.
- **Non-Target-Site Resistance Management:** Using herbicides with diverse chemistries helps avoid metabolic resistance, where weeds degrade or sequester the herbicide before it can act.

For instance, in Brazil, the integration of herbicides targeting both EPSPS (Glyphosate) and HPPD pathways has shown success in managing resistant weeds like *Conyza bonariensis*.

Non-Chemical and Integrated Weed Management

Non-chemical and integrated weed management (IWM) strategies have gained prominence as sustainable alternatives to conventional herbicide-based approaches in agriculture. These methods combine mechanical, cultural, and biological practices to effectively suppress weed populations while minimizing environmental impact and reducing reliance on chemical herbicides.

Mechanical weed control involves physical methods such as tillage, mowing, and hand weeding to remove or destroy weeds. A study by Melander *et al.* (2013) [3] demonstrated that mechanical weeding, when timed appropriately, can achieve weed control levels comparable to chemical methods,

particularly in row crops like soybeans and maize. However, the effectiveness of mechanical control is highly dependent on factors such as weed species, growth stage, and environmental conditions.

Cultural practices, including crop rotation, cover cropping, and adjusting planting densities, enhance crop competitiveness against weeds. Liebman and Davis (2000) [2] found that diverse crop rotations disrupt weed life cycles and reduce weed seed banks, leading to lower weed pressure over time. Cover crops, such as cereal rye, have been shown to suppress weeds through allelopathy and by creating a physical barrier that inhibits weed emergence (Teasdale *et al.*, 2007) [7].

Biological control utilizes natural enemies of weeds, such as insects, pathogens, or grazing animals, to reduce weed populations. For instance, the use of fungal pathogens like *Colletotrichum gloeosporioides* has been explored for controlling specific weed species (Charudattan, 2001) [1]. While promising, biological control methods often require extensive research to ensure specificity and effectiveness without unintended ecological consequences.

Integrated Weed Management (IWM) combines multiple control strategies to manage weeds more sustainably. Norsworthy *et al.* (2012) [6] emphasized that integrating cultural, mechanical, and chemical methods can delay the development of herbicide resistance and provide more robust weed control. For example, combining cover cropping with reduced herbicide applications has been effective in managing resistant weed populations (Mirsky *et al.*, 2013) [4].

The adoption of non-chemical and integrated approaches requires careful planning and consideration of local conditions, including climate, soil type, and prevalent weed species. While these methods can reduce reliance on herbicides and promote environmental sustainability, they may also involve increased labor and management complexity. Ongoing research and extension services are crucial to developing and disseminating effective IWM practices tailored to specific cropping systems and regions.

Conclusion

The study highlights the growing importance of non-chemical and integrated weed management (IWM) strategies as sustainable alternatives to conventional herbicide-based methods. These approaches not only address the challenges posed by herbicide-resistant weed populations but also promote environmental sustainability and long-term agricultural productivity. Mechanical, cultural, and biological control methods, when effectively combined within an IWM framework, can provide robust weed suppression while reducing reliance on chemical herbicides.

Research findings indicate that practices such as crop rotation, cover cropping, mechanical interventions, and the use of biological agents offer significant potential for mitigating weed pressure without compromising yield. The integration of these methods with reduced herbicide applications delays resistance development and enhances the ecological balance of farming systems. However, successful implementation of these strategies requires careful planning, local adaptation, and increased farmer awareness.

The adoption of IWM is not without challenges, including higher labor demands, management complexity, and the need for targeted research. Nonetheless, ongoing innovations in precision agriculture, as well as education and extension efforts, will be critical in overcoming these barriers. By leveraging diverse and complementary weed control strategies, IWM offers a practical

and sustainable path forward for modern agriculture, ensuring both productivity and environmental stewardship.

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