



Herbicides in Modern Farming Balancing Sustainability with Environmental and Health Issues

*Dr. Madhurjit Singh Rathore¹, Madhudwisha Chetia², Subhashree Samantaray³,
Nikkondi Chandra Prabha⁴ and Durgesh Kumar Maurya⁵

¹Young Professional II, Department of Biotechnology, Rajmata Vijayaraje Scindia
Krishi Vishwavidyalaya, Gwalior, Madhya Pradesh, India

²M. Sc. Scholar, Department of Agronomy, School of Agricultural Sciences, Nagaland
University, Nagaland, India

³Research Scholar, Department of Agronomy, Palli Siksha Bhavana, Institute of
Agriculture, Visva-Bharti, Sriniketan, West Bengal, India

⁴M.Sc. Scholar, Department of Genetics and Plant Breeding, Odisha University of
Agriculture and Technology, Bhubaneswar, Odisha, India

⁵SMS, Department of Agronomy, KVK, Bagahi, Santkabirnagar, Uttar Pradesh, India

*Corresponding Author's email: madhur1691946@gmail.com

Herbicides play an essential role in contemporary agriculture by effectively managing weed populations and supporting sustainable crop yields. Nonetheless, their widespread use has raised environmental and food safety concerns due to potential contamination and its harmful effects on ecosystems and biodiversity. While recent data show a reduction in overall herbicide usage, there is a noticeable shift toward more precise and targeted formulations, including increased application of systemic and pre-emergence herbicides. Despite these advancements, global agriculture continues to face significant challenges related to the ecological consequences of herbicide contamination, both at the site of application and beyond. Addressing these issues requires the development of herbicides with improved selectivity or environmentally friendly, biodegradable alternatives that minimize long-term environmental risks. Additionally, implementing integrated weed management strategies offers a sustainable solution to curb the spread of herbicide-resistant weeds, avoiding the pitfalls of continuous herbicide reliance. This review serves as a comprehensive resource, highlighting current trends, potential risks, and future directions in herbicide use, with particular emphasis on human health, food safety, technological innovation, regulatory frameworks, and sustainable alternatives—providing valuable insights for agroecologists, policymakers, and agricultural stakeholders alike.

Introduction

The global population is projected to rise to 9.2 billion by 2050, creating a pressing need for a 70% boost in agricultural productivity to maintain food security. Around half of the world's usable land is already devoted to farming, where growers must contend with various challenges such as weeds, insect pests, and fungal infections. Among these, weeds are particularly detrimental, as they compete with crops for vital resources like nutrients, sunlight, space, and water—often resulting in yield losses ranging from 20% to 50%, depending on their severity and duration in the field.

To manage weeds, farmers utilize a range of strategies, including manual, mechanical, and chemical methods. Of these, chemical weed control has emerged as the most efficient and widely adopted approach due to rising labor costs, the demand for rapid action, and the overall goal of maximizing productivity at lower expense. As a result, herbicides have

become a fundamental component of modern farming practices, aiding in both crop production and weed suppression in non-crop areas.

Globally, pesticide use exceeds 4 million tons annually, with herbicides making up nearly half of that total. Since the mid-20th century, more than 200 active herbicidal ingredients have been utilized in both industrialized and developing nations, driven by growing demand and economic expansion, particularly in agriculture and industry.

Despite their benefits, herbicides also pose serious environmental and health risks. Their presence in soil, air, water, and food systems can negatively affect humans, animals, and entire ecosystems. Improper use can leave residues in crops and soils, cause toxicity, promote herbicide-resistant weed populations, and harm non-target organisms. These chemicals can also migrate from application sites to surrounding environments through runoff, leaching, or volatilization, leading to long-term contamination and potential health hazards.

With the intensification of agriculture over the past decade, there has been a noticeable shift toward advanced technologies, including the development of new herbicide molecules, adoption of herbicide-resistant crops, and cultivation of more competitive crop varieties. The use of systemic and pre-emergence herbicides has become more prevalent. Systemic herbicides penetrate and circulate through a plant's internal system, delivering broad and effective control. Pre-emergence herbicides, applied before weeds appear, help prevent their growth, reduce competition, and improve yields while decreasing reliance on post-emergence treatments.

Trends also show a decline in broad-spectrum herbicide use, with a growing preference for more specific, targeted formulations that limit damage to desirable crops and reduce overall chemical input. Another key development in weed control strategies is the focus on lowering weed seed bank levels in the soil to prevent future infestations.

Importance of herbicides in modern agriculture

Weeds are a major challenge in modern agriculture, significantly reducing both the yield and quality of crops, and causing annual losses worth billions of dollars worldwide. In fact, the damage caused by weeds is greater than that caused by other agricultural pests such as insects, diseases, nematodes, and rodents. It is estimated that weeds are responsible for nearly half of all crop losses, posing a substantial threat to global food security. For instance, in the United States alone, weed-related damage is estimated to exceed \$26 billion each year.

To combat this issue, herbicides have become the most effective solution, offering a quick, economical, and highly efficient method of weed control. Modern herbicides can eliminate up to 90–99% of targeted weed species, making them a vital tool for improving crop yields and supporting global food demands. Over the past century, the use of herbicides has expanded dramatically, and they now make up nearly half of all pesticide usage worldwide. Thousands of herbicidal compounds have been developed for use across various farming systems and are applied either to the soil during field preparation or directly onto plant foliage.

There are two main types of herbicide applications: pre-emergence and post-emergence. Pre-emergence herbicides are applied to the soil to target weed seeds before they sprout, whereas post-emergence herbicides are sprayed on weeds after they have emerged from the soil. Both types are available in a variety of chemical formulations designed to target specific weeds without harming crops. Herbicides are further classified by their mode of action—the specific biological process they disrupt—and by their chemical family, which groups herbicides based on similar molecular structures.

In addition to weed control, herbicides are also used as plant growth regulators in agricultural and horticultural settings. For example, in small doses, some herbicides can promote plant growth, help in crop ripening, or even protect against certain diseases in herbicide-resistant plant varieties. In recent times, the reliance on herbicides has grown even more due to increasing labor costs and occasional shortages of farmworkers. As a result, herbicides have become an indispensable part of modern farming for managing unwanted weeds and maintaining agricultural productivity.

Recent trends in weed management

In recent years, herbicide usage patterns have drawn considerable attention within the agricultural sector. The effects of herbicides on human and environmental health, as well as their mode of action, vary depending on their chemical composition. A notable trend over the past decade has been the gradual reduction in the total volume of herbicides used, alongside a move toward more precise and selective formulations. This change is largely driven by growing awareness of the environmental and health risks linked to widespread herbicide use. At the same time, advancements in precision agriculture have enabled more accurate and efficient herbicide application. These developments offer valuable guidance for farmers, regulators, and agricultural industries, supporting the creation of herbicide management strategies that effectively control weeds while minimizing ecological impact.

Increased application of systemic herbicides

In recent times, systemic herbicides have become increasingly popular due to their high effectiveness in managing weed populations. Glyphosate, for example, has been widely used across different crop systems for decades because of its broad-spectrum weed control capabilities. However, its extensive use has led to the emergence of glyphosate-resistant weed species, highlighting the need for alternative herbicides and improved management practices. Other systemic herbicides, such as dicamba and 2,4-D, have also gained prominence for controlling broadleaf weeds, particularly in crops like soybean and cotton, including those genetically engineered to tolerate these chemicals. Despite their effectiveness, both dicamba and 2,4-D have raised concerns due to their potential to drift beyond the intended application area, which can cause unintended damage to nearby sensitive crops and vegetation. These concerns have led to regulatory restrictions on their use in some areas.

Glufosinate is another widely used non-selective systemic herbicide, commonly applied in herbicide-tolerant varieties of corn, soybean, and cotton. It has emerged as a popular alternative to glyphosate in certain situations. However, the growing presence of glufosinate-resistant weeds poses a significant challenge that demands attention.

As agricultural practices continue to advance, it is crucial to confront these emerging issues by adopting innovative weed management strategies and exploring sustainable herbicide alternatives. This will be essential to maintaining effective weed control and ensuring the long-term viability of modern farming systems.

Increased use of pre-emergence herbicides

In recent years, there has been a clear trend toward the increased use of pre-emergence herbicides in agriculture. These herbicides are applied to the soil before the crop appears, targeting weed seeds and young seedlings before they can emerge. This approach has proven to be highly effective, often offering better weed control than post-emergence treatments. The growing preference for pre-emergence herbicides can be attributed to several benefits, including enhanced effectiveness, reduced competition between weeds and crops for essential resources like nutrients, water, and light, lower risk of developing herbicide-resistant weed populations, and improved crop safety.

One of the major challenges in modern farming is the development of herbicide-resistant weeds. By incorporating pre-emergence herbicides into weed control programs, farmers can diversify their methods of action, which helps delay resistance and maintain herbicide efficacy over time. Since these herbicides are applied before the crop emerges, they allow for precise targeting in the soil where weed seeds are located. This timing reduces the likelihood of damaging young crops, thus enhancing crop protection.

Several types of pre-emergence herbicides have become widely adopted in agricultural practices. Group 14 herbicides, such as sulfentrazone and flumioxazin, and Group 15 herbicides, like acetochlor, metolachlor, and S-metolachlor, are commonly used to control both broadleaf and grassy weeds in crops such as corn, soybeans, cotton, and peanuts. Group 5 herbicides, including metribuzin and flumioxazin, are valued for their broad-spectrum control in crops like potatoes, soybeans, and peas. Meanwhile, Group 3 herbicides,

such as pendimethalin and trifluralin, are especially effective against grassy weeds and are widely used in crops like corn, wheat, and various vegetables.

As a result, pre-emergence herbicides from Groups 3, 5, 14, and 15 have become essential tools in integrated weed management programs, ensuring effective control of a wide range of weed species across different crop systems.

Use of genetically modified herbicide-resistant crops

The adoption of genetically modified (GM) herbicide-resistant crops has become a significant development in agricultural weed management over the past few decades. These crops are specifically engineered to withstand certain herbicides, enabling farmers to control weeds more effectively without harming the cultivated plants. Among the most widely accepted are glyphosate-resistant varieties of crops such as soybeans, corn, cotton, and canola. Their introduction has led to a greater dependence on glyphosate-based products, like Roundup®, offering farmers improved flexibility, ease of weed control, higher yields, and reduced labor expenses.

Beyond glyphosate, crops resistant to other herbicides—such as glufosinate, dicamba, and 2,4-D—have also been developed and adopted in various agricultural regions. These herbicide-tolerant crops expand farmers' weed control options and support better resistance management by encouraging herbicide rotation and reducing dependence on a single chemical mode of action.

While GM herbicide-resistant crops offer several advantages, including enhanced weed suppression, better crop productivity, and the potential to reduce soil disturbance through less tillage, they also raise concerns. Chief among them is the emergence of herbicide-resistant weed species, which can result from the repeated use of the same herbicide over time. This growing issue underscores the importance of implementing integrated weed management strategies that combine various approaches to weed control.

In summary, although GM herbicide-resistant crops have revolutionized agricultural weed management, it is crucial to adopt sustainable practices that minimize environmental risks and delay resistance development. Doing so is vital for maintaining long-term agricultural productivity, food safety, and environmental health.

Herbicide resistance in weeds

Emergence of herbicide-resistant weed species

Herbicide-resistant weeds are becoming an increasing global concern, posing a serious threat to food security. The repeated and long-term use of the same herbicide, especially those with the same mode of action, has led to changes in weed populations, making them resistant. This issue has become more prominent since the introduction of genetically modified (GM) herbicide-resistant crops, particularly with the widespread use of glyphosate. Over time, resistant weeds reproduce and dominate, making them harder to control.

Several factors influence the development of herbicide resistance, including the type of herbicide, application rates, and non-chemical factors. The first known case was reported in 1957 when wild carrot developed resistance to 2,4-D in Canada. Since then, more than 200 weed species worldwide have shown resistance to one or more herbicides, with the highest numbers reported in the USA, followed by Australia, Canada, France, and China.

Notable resistant species include wild radish in Australia, prickly lettuce in the USA, and corn poppy in Europe. Glyphosate-resistant weeds, such as *Lolium rigidum* and *Eleusine indica*, emerged soon after the introduction of glyphosate-resistant crops in 1996, largely due to excessive use—sometimes applied 5 to 10 times a year for over a decade. The continued rise of herbicide-resistant weeds remains a major challenge for global crop production and ecosystem health.

Mechanisms of herbicide resistance

Herbicide resistance has become a major obstacle in modern agriculture, reducing the effectiveness of weed control. Several mechanisms contribute to this issue, with one of the most common being target-site resistance. This occurs when genetic mutations alter the

specific proteins or enzymes that herbicides target, making them less responsive. These changes can result from spontaneous mutations or repeated herbicide exposure and may involve altered proteins, gene amplification, or overexpression.

Another key mechanism is metabolic resistance, where weeds break down or detoxify herbicides more efficiently, lowering their impact. This is often due to increased activity of enzymes like cytochrome P450s, glutathione transferases, or esterases. Weeds may also resist herbicides by limiting their uptake or movement within the plant, often due to changes in membrane function or transport systems.

In some cases, weeds develop multiple resistance by acquiring resistance to more than one herbicide, either through accumulating different resistance traits or through gene transfer between species. Understanding these resistance mechanisms is essential for developing effective strategies to manage herbicide-resistant weed populations.

Environmental implications of herbicide use in modern agriculture

The environmental toxicity of herbicides is influenced by several factors, including their chemical properties, soil conditions, climate, application methods, frequency of use, and environmental characteristics. The addition of adjuvants, while improving herbicide performance, can increase toxicity and lead to more persistent residues in soil and crops, as seen with higher trifluralin residues in sugar beet roots. Accumulation of herbicides, especially in aquatic systems near agricultural areas, further raises environmental concerns. Therefore, it is essential to monitor the movement and behavior of herbicides in agricultural soils to assess their ecological impact and minimize harm to non-target organisms and ecosystems.

Mobility of herbicides in the environment

Herbicides can move from agricultural fields into the broader environment through spray drift, volatilization, runoff, and leaching, posing risks to non-target organisms, human health, and ecosystems. Research shows that only about 45% of sprayed herbicides reach their intended targets, while the rest is lost through drift, runoff, leaching, and deposition into the soil. Runoff occurs when herbicides are carried by water over sloped surfaces, influenced by factors like soil type, moisture, topography, and weather. Leaching, the downward movement of herbicides through soil, threatens groundwater, especially in sandy soils or when herbicides are water-soluble and poorly bound to soil particles. Volatilization, another significant route, involves the evaporation of herbicides into the atmosphere, often increased by hot, dry, or windy conditions and fine spray droplets. These volatilized chemicals can travel long distances and settle in water bodies, increasing environmental contamination. Additionally, other pollutants like PAHs may accumulate in soils over time. As climate change intensifies, with rising temperatures and altered rainfall patterns, these challenges are expected to worsen. Therefore, integrating sustainable weed and resource management practices is essential to minimize environmental harm and protect long-term agricultural productivity.

Persistence/degradation of herbicides in the environment

The persistence of herbicides in soil, plants, water, and air is a growing global concern due to their potential to remain long after application, leading to food toxicity and environmental harm. Herbicides are classified by their half-life (DT₅₀), indicating how long they take to degrade—ranging from non-persistent (under 1 month) to long-lasting (over 6 months). Repeated use of the same herbicides slows degradation, increasing the risk of accumulation and contamination, especially in groundwater and surrounding ecosystems. Certain herbicide groups like triazines, sulfonyleureas, and dinitroanilines are known for their persistence.

Degradation is the main way herbicides are removed from the environment, occurring through biotic (microbial) and abiotic (chemical or sunlight) processes. Microorganisms such as bacteria and fungi play a major role by using herbicides as sources of energy or nutrients, especially in warm, moist, and organic-rich soils. In extreme soil pH conditions, abiotic degradation becomes more dominant through processes like hydrolysis or oxidation. Photodegradation by sunlight also breaks down herbicides, particularly those with specific

chemical structures, but is generally slower in water than in soil. Various factors—such as soil type, organic content, pH, herbicide properties, climate, and vegetation—affect the degradation rate. In some conditions, like low microbial activity, herbicides such as glyphosate can persist in soil for months, emphasizing the need for careful management to avoid long-term environmental impacts.

Food safety concern of herbicide residues

Herbicide use in agriculture presents several issues, including overuse, incorrect application, and harvesting crops too soon after spraying, which can lead to high chemical residues in food. These residues, depending on exposure levels, pose risks to human health, as food is a primary route for herbicides to enter the body. Most countries monitor residue levels using Maximum Residue Limits (MRLs) to ensure food safety. However, studies have found herbicide residues exceeding MRLs in cereals, vegetables, and root crops across various countries, including India, Korea, Nigeria, and Australia. For example, glyphosate and 2,4-D have been detected in spinach, lettuce, wheat, and cassava at levels above safety thresholds. Herbicides applied close to harvest time increase the chance of residue accumulation in food, especially in raw-consumed fruits and vegetables. Even low-level exposure over time can lead to chronic health effects. As a result, there is growing consumer demand for residue-free produce, highlighting the need to enforce good agricultural practices (GAP) and regularly monitor residues to protect food safety and public health.

Conclusion

Herbicides play a vital role in global modern agriculture, yet their improper and excessive use poses serious risks to both human health and the environment. Prolonged application can lead to the emergence of herbicide-resistant weed species, while runoff and leaching contribute to the contamination of surface and groundwater, harming aquatic ecosystems. Although there is a growing trend toward more precise and targeted herbicide formulations, along with increased use of systemic and pre-emergence products and a reduction in total usage, the environmental challenges remain significant. To address these issues, it is essential to develop herbicides with higher selectivity or eco-friendly, bio-based alternatives. Innovations such as enzyme inhibitors and receptor-targeted herbicides can offer effective weed control with minimal environmental impact. Additionally, formulations that rapidly degrade or bind tightly to soil can help prevent water contamination. Embracing sustainable weed management through technologies like remote sensing, drones, and machine learning can support accurate weed detection and targeted application. Raising public awareness and encouraging informed discussions among farmers, consumers, and stakeholders are also key to promoting safe herbicide use.

References

1. Abouziena H, Haggag W (2016) Weed control in clean agriculture: a review. *Planta Daninha* 34:377–392.
2. Baiu I, Visser B (2018) Gallbladder cancer. *Jama* 320:1294–1294.
3. Duke SO, Powles SB (2008) Glyphosate: a once-in-a-century herbicide. *Pest Manag Sci* 64:319–325.
4. Friesen H (1965) The movement and persistence of dicamba in soil. *Weeds* 13:30–33.
5. John S, George S, Primrose J, Fozard J (2011) Symptoms and signs in patients with colorectal cancer. *Colore Dis* 13:17–25.
6. Parween T, Jan S, Mahmooduzzafar S, Fatma T, Siddiqui ZH (2016) Selective effect of pesticides on plant—a review. *Crit Rev Food Sci Nutri* 56:160–179.
7. Tiryaki O, Temur C (2010) The fate of pesticide in the environment. *J Biol Environ Sci* 4:29–38.