



International Journal of Research in Agronomy

E-ISSN: 2618-0618
P-ISSN: 2618-060X
© Agronomy
NAAS Rating (2026): 5.20
www.agronomyjournals.com
2026; SP-9(3): 62-69
Received: 22-01-2026
Accepted: 25-02-2026

Athul Prasad
Department of Agronomy, Faculty
of Agricultural Sciences, Shree
Guru Gobind Singh Tricentenary
University, Gurugram, Haryana,
India

Sayooj M
Department of Genetics and Plant
Breeding, College of Agriculture,
Kerala Agricultural University,
Vellayani, Thiruvananthapuram,
Kerala, India

Yash
Department of Agronomy, Faculty
of Agricultural Sciences, Shree
Guru Gobind Singh Tricentenary
University, Gurugram, Haryana,
India

Tati Saketh Chowdary
Department of Agronomy, Faculty
of Agricultural Sciences, Shree
Guru Gobind Singh Tricentenary
University, Gurugram, Haryana,
India

Corresponding Author:
Athul Prasad
Department of Agronomy, Faculty
of Agricultural Sciences, Shree
Guru Gobind Singh Tricentenary
University, Gurugram, Haryana,
India

Herbicide persistence and its management: Implications for agriculture and the environment

Athul Prasad, Sayooj M, Yash and Tati Saketh Chowdary

DOI: <https://www.doi.org/10.33545/2618060X.2026.v9.i3Sa.5014>

Abstract

Persistence of herbicides refers to the period during which herbicides are active in the environment and is an important factor in both weed control and environmental health. Herbicides are one of the important tool for managing weeds in agricultural ecosystems, but persistence in soil, water, and non-target habitats can be problematic. Long-term persistence may result in the buildup of herbicides in the soil, affecting plant growth, injuring beneficial organisms, and even contaminating water bodies, which can impact ecosystems and human health. Chemical structure, environmental factors (e.g., temperature, rainfall), soil type, and microbial activity affect the duration for which herbicides are active. This paper discusses the consequences of herbicide persistence to agriculture, taking into consideration the impact on crop yield, soil quality, and water. It also points to the environmental danger posed by enduring herbicide residues, which has the potential to lead to the loss of biodiversity and food-chain contamination. In response, several management options are investigated to reduce herbicide persistence, such as optimizing application methodology, rotating herbicide modes of action, employing more environmentally friendly herbicides, and implementing integrated pest management (IPM) approaches. Moreover, the need for the development of regulatory systems and promotion of farmer education of herbicide management is addressed. Finally, the paper stresses the importance of an integrated approach that optimizes weed control effectiveness and reduces long-term environmental impacts, promoting agricultural productivity and ecosystem conservation for generations to come.

Keywords: Herbicides, integrated pest management, persistence, weeds

Introduction

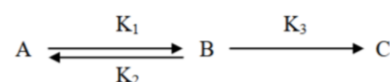
Herbicides play an important role in modern agriculture by reducing weed pressure and thereby improving crop productivity. Persistence is the time a herbicide persists in the environment before it is degraded by microbial, chemical, or physical processes. However, their persistence in soil and water has raised significant environmental concerns, like their prolonged persistence can cause carryover damage to crops, groundwater contamination, and disruption of soil microbes. Herbicide fate depends on factors like chemical structure, mode of action, soil adsorption, microbial degradation, and climate. Some degrade quickly, while others persist for months or years. Soil properties, moisture, pH, and microbial activity play key roles in their persistence and breakdown. (Maia *et al.*, 2024 and Babal *et al.*, 2020) ^[23, 5] had stated that when herbicides remain in the environment for extended periods, they may affect non-target organisms, alter soil microbial communities, and contaminate surface and groundwater resources. India is the third-largest pesticide consumer globally and the highest in South Asia (Agnihotri, 2000) ^[1]. Among pesticide groups, herbicides have shown the fastest growth (24.8%) over the past two decades. However, their excessive use leaves residues in soil, water, and crops, posing environmental risks. Understanding herbicide persistence is therefore essential for safe use and for developing sustainable weed management programs. Sumekar *et al.*, (2023) ^[34] had suggested that the extent of persistence largely depends on several factors, including the chemical properties of the herbicide, soil characteristics, climatic conditions, and management practices. For example, herbicides with low degradability or high adsorption to soil particles may accumulate and interfere with soil health and crop growth. Such residues can also reduce the effectiveness of crop rotations and lead to herbicide resistance in weed populations (Alferez

et al., 2019)^[2]. Understanding herbicide persistence is therefore essential for developing sustainable weed management programs. Studies have shown that conservation agriculture, cover cropping, and organic matter management can significantly reduce herbicide residues in soil (Babal *et al.*, 2020; Maia *et al.*, 2024)^[5, 23]. At the same time, assessing the environmental impact of different herbicides helps in designing safer application schedules and minimizing risks to ecosystems and human health (International Journal of Environmental Science and Technology, 2024). Hence, research on herbicide persistence and its management is critical for achieving a balance between effective weed control and environmental protection. Such knowledge will enable farmers and policymakers to develop chemical weed control strategies that are both productive and ecologically sustainable. Recent research emphasizes that integrating ecological and agronomic principles can mitigate herbicide persistence. Studies have shown that conservation agriculture, cover cropping, and organic matter management can significantly reduce herbicide residues in the soil, enhancing degradation through improved microbial activity and soil structure (Babal *et al.*, 2020; Maia *et al.*, 2024)^[5, 23]. Likewise, the adoption of precision agriculture tools and integrated weed management (IWM) practices can help optimize herbicide dosages, application timing, and placement, minimizing off-target losses and environmental hazards. Evaluating the environmental impact of different herbicides is therefore crucial for designing safer application schedules and minimizing risks to ecosystems and human health (International Journal of Environmental Science and Technology, 2024). Regulatory frameworks and residue monitoring programs play a key role in ensuring that herbicide use remains within permissible limits. Moreover, promoting awareness among farmers about safe handling, appropriate dosage, and post-application management can further mitigate environmental contamination. Hence, research on herbicide persistence and its management remains critical for achieving a balance between effective weed control and environmental protection. Such knowledge will enable farmers, researchers, and policymakers to develop herbicide-based weed control strategies that are productive, economically viable, and ecologically sustainable. A deeper understanding of herbicide behavior in different agroecosystems will ultimately contribute to resilient agricultural systems that safeguard both food security and environmental health.

Understanding Herbicide Persistence: Agricultural and Environmental Implications

The word persistence was first used in pesticide science to explain how certain insecticides remain in the environment for extended periods. Today, the term is applied more broadly to any organic chemical with biological activity. In reality, some level of degradation almost always happens. In fact, a certain degree of persistence is often beneficial, because it ensures that the chemical continues to act for the intended period. The extent to which herbicide or pesticide is considered persistent depends both on its inherent chemical properties and on the specific conditions of the environment in which it is applied. Among these properties, organic matter influences almost all the physical, chemical and biological properties of soil, most often interrelated with each other, thus, affecting the fate of applied herbicide in soil (Chirukuri and Atmakuru, 2014)^[8]. (Greenhalgh *et al.*, 1980)^[16] suggested that it can be expressed in units of time or dimension-less units relative to a benchmark. Kearney *et al.* (1969)^[19] reported that the persistence is defined

as the time required for reducing the pesticidal concentration in soil to 75 to 100 per cent of the amount initially added. According to Furmide and Osgerby (1967)^[13] this is explained by following equation as:



Where, A-Soil-pesticide adsorption complex,
B-Pesticides in solution and
C-Decomposition,

K-is independent of soil type or its value is the same within the soil as that in an aqueous solution at the same pH and temperature in the absence of soil, if the degradation is only chemical.

From an environmental perspective, herbicide persistence is a concern because residues can leach into groundwater or run off into surface water bodies, where they may accumulate and negatively affect aquatic ecosystems. Persistent chemicals can also alter soil microbial communities, reduce biodiversity, and interfere with essential soil processes such as nutrient cycling. Another major consequence of prolonged herbicide activity is the increased risk of resistance development in weed populations, which threatens the long-term effectiveness of weed management strategies and often forces farmers to rely on stronger or multiple herbicides.

Studying persistence is equally important from the viewpoint of food safety and human health. Residues that remain in soil or on crops may enter the food chain, exposing humans and animals to herbicides over long periods. Even when exposure levels are low, persistence increases the likelihood of chronic effects. This is why regulatory agencies set residue limits and pre-harvest intervals based on persistence studies. For scientists, understanding persistence provides essential information for herbicide selection, timing of application, crop rotation planning, and the design of integrated weed management strategies. It also guides environmental risk assessments and policymaking, ensuring that weed control practices remain both productive and sustainable.

The persistence of herbicide in the soil is determined by the degree of its adsorption, the mobilization and the degradation. The adsorption of the herbicide by organic and inorganic collides of the soil temporarily removes the herbicide solution from the soil. This reduces the biological activity or concentration of the herbicide in the soil. The biological activity of herbicides is reduced by microbial decomposition, chemical inactivation, plant absorption and decomposition, volatilization, leaching and runoff.

Factors influencing herbicide persistence

1. **Soil Texture:** Soil texture greatly influences herbicide behaviour because it controls both adsorption and mobility. Sandy soils, with large pores and low surface area, allow herbicides to leach more easily, resulting in shorter persistence in the topsoil. In contrast, clay-rich soils provide more binding sites, which can slow down degradation but retain herbicides for longer periods, sometimes leading to carryover effects (Singh *et al.*, 2018)^[32].
2. **Soil pH:** Soil pH regulates the chemical form of herbicides and affects how strongly they bind to soil particles. Weak acid herbicides, such as sulfonylureas, are more soluble and mobile in alkaline soils, increasing the risk of crop injury

and water contamination. On the other hand, acidic soils often reduce solubility, leading to greater adsorption and reduced bioavailability for microbial degradation (Alletto *et al.*, 2010) ^[3]. Thus, pH indirectly alters persistence by modifying both chemical and biological processes.

3. **Soil Organic Matter:** Organic matter (OM) is a critical factor in determining herbicide persistence. Many herbicides bind strongly to humic substances in soil, reducing their immediate mobility but also making them less available for microbial attack. This can prolong their half-life under field conditions. However, organic amendments such as compost or biochar may either enhance degradation by stimulating microbial growth or immobilize herbicides, depending on the compound and soil type (Wauchope *et al.*, 2002) ^[36].
4. **Soil Moisture and Aeration:** Moisture availability strongly influences both chemical reactions (like hydrolysis) and biological degradation. Under well-aerated and moist conditions, microbial activity is stimulated, leading to faster breakdown of herbicides. In contrast, prolonged drought conditions suppress microbial metabolism, while waterlogged soils reduce oxygen availability, slowing degradation pathways and sometimes favoring more persistent anaerobic metabolites (Stork *et al.*, 2008) ^[33]. Thus, both excess and deficit moisture can increase persistence.
5. **Soil Temperature:** Temperature is a key driver of herbicide dissipation. Higher soil temperatures generally accelerate

both chemical and biological processes, thereby reducing the half-life (DT₅₀) of herbicides. Seasonal differences often explain why certain herbicides persist longer in winter compared to summer under the same soil conditions. Extremely low temperatures slow microbial activity, whereas excessively high temperatures may reduce microbial diversity, altering degradation pathways (Walker *et al.*, 2001) ^[35].

6. **Microbial Activity:** Microorganisms are the primary agents of herbicide breakdown in many soils. Specific bacteria and fungi possess enzymes that can mineralize or transform herbicides into less harmful compounds. The extent of persistence often depends on whether the soil community has adapted to degrade the compound. In some cases, repeated application of the same herbicide promotes "enhanced biodegradation," where specialized microbes increase degradation rates over time (Singh, 2016) ^[30].
7. **Sorption-Desorption Dynamics:** The balance between sorption and desorption processes determines herbicide bioavailability. Strong sorption to clay particles or organic matter reduces immediate leaching but also protects the herbicide from degradation, potentially increasing its persistence. On the other hand, weakly sorbed herbicides remain more available for microbial and chemical transformation but are also more prone to leaching. Understanding sorption-desorption is therefore crucial when predicting environmental behavior (OECD, 2002) ^[25].

Table 1: Herbicides and their persistence in soil. (Common herbicide groups - William S. Curran, Ph.D. <https://extension.psu.edu/persistence-of-herbicides-in-soil>.)

Herbicide	Soil Adsorption (K _{oc})	Leaching Potential	Half-life (days)	Remarks
Pendimethalin	Very High (>3000)	Very Low	90-120	Strong adsorption, minimal leaching.
Pyroxasulfone	Moderate (100-500)	High	100-150	Can leach in sandy soils, long residual effect.
Flufenacet	Moderate (200-600)	Moderate	60-100	Moves moderately in soil, effective for early weed control.
Trifluralin	Very High (>5000)	Very Low	45-75	Strongly binds to soil, highly volatile.
Metolachlor	Low to Moderate (50-200)	High	40-60	Mobile in soil, higher leaching potential.

Herbicide degradation

Herbicide degradation is the breakdown of herbicides into less active forms through microbial, chemical, and photodegradation processes. Amritha (2017) ^[4] reported that microbial biomass and soil enzymes accelerate degradation, especially in soils with good organic matter. Singh *et al.* (2018) ^[32] noted that bacteria and fungi play a key role in degrading sulfonylurea and triazine herbicides. Chemical degradation also contributes, as Chand (2018) ^[7] observed faster hydrolysis of flucetosulfuron in acidic soils. Surface-applied herbicides undergo photodegradation under sunlight, which is significant in tropical regions Basu & Rao, (2020) ^[6]. Environmental factors such as soil pH, temperature, and moisture strongly affect the rate of degradation. For example, Leoci & Ruberti (2020) ^[22] found glyphosate degradation slows under dry or cold conditions. Management practices like adding organic amendments improve microbial activity and shorten herbicide half-life Mohammad Mehdi-zadeh (2019) ^[24].

Herbicide degradation pathways

1. **Microbial Degradation:** Microbial degradation is the primary pathway for herbicide dissipation in soils, where bacteria and fungi use herbicides as a carbon and energy source. Microorganisms such as *Pseudomonas* and *Bacillus* species are involved in this process, leading to either complete mineralization or partial breakdown. Studies have

shown that soil type, organic matter, and environmental conditions strongly influence microbial activity and degradation rates (Singh & Walker, 2006) ^[31].

2. **Chemical Degradation:** Chemical degradation occurs through abiotic processes such as hydrolysis, oxidation, and reduction that break down herbicide molecules in the soil. These processes are highly dependent on soil pH, temperature, and moisture. For instance, sulfonylurea herbicides degrade faster in acidic soils via hydrolysis. Chemical hydrolysis has been identified as a key degradation pathway for atrazine and sulfonylureas under specific soil conditions (Krutz *et al.*, 2008) ^[20].
3. **Photodegradation:** Photodegradation is the breakdown of herbicides by sunlight, mainly through photolysis reactions at the soil or water surface. The extent of this process depends on solar intensity and the herbicide's chemical structure. Surface-applied herbicides like paraquat and atrazine are particularly prone to photodegradation when exposed to direct sunlight (Kudsk & Streibig, 2003) ^[21].
4. **Volatilization and Leaching:** Volatilization is the loss of herbicides into the atmosphere due to their vapor pressure, while leaching is the downward movement of herbicides through the soil profile, often leading to groundwater contamination. Soil texture, rainfall, and solubility of the herbicide strongly affect these processes. Volatile herbicides such as EPTC and trifluralin are highly prone to

atmospheric losses, whereas soluble herbicides like atrazine and metribuzin often leach into groundwater (Gish *et al.*, 1995)^[15].

Environmental and agronomic effects of herbicide persistence

- 1. Carryover Injury to Rotational Crops:** One of the major agronomic effects of herbicide persistence is carryover injury to crops grown in rotation. Residual herbicides in soil can negatively affect sensitive crops, reducing germination, root growth, and yield. For example, sulfonylurea herbicides often remain active for months and may injure legumes or oilseeds planted after cereals (Shaner & Henry, 2007)^[29].
- 2. Soil Health and Microbial Activity:** Herbicide residues can also alter soil microbial communities and enzyme activities, which play a crucial role in nutrient cycling and soil fertility. While some microbes can adapt and degrade herbicides, others may be suppressed, leading to reduced soil health and slower organic matter turnover (Rose *et al.*, 2016)^[27].
- 3. Groundwater and Surface Water Contamination:** Persistent herbicides are prone to leaching and runoff, which may contaminate groundwater and nearby rivers or ponds. Atrazine, metribuzin, and simazine are frequently detected in water bodies, raising concerns about water quality and safe drinking water (Gilliom, 2007)^[14].
- 4. Food Chain and Ecosystem Effects:** Herbicide residues can enter the food chain through plants, soil organisms, and water systems, affecting non-target species and ecosystem balance. Long-term exposure has been linked to reduced

biodiversity, bioaccumulation in aquatic organisms, and potential risks to human health through food consumption (Duke, 2012)^[10].

Herbicide residue analysis

- 1. Methods of Detection:** Detection of herbicide residues relies on advanced analytical tools. High-Performance Liquid Chromatography (HPLC) and Gas Chromatography–Mass Spectrometry (GC-MS) are the most widely used because they offer high accuracy and sensitivity. In addition, bioassays are sometimes used as a low-cost method to detect phytotoxic residues in soil or water, though they are less precise compared to chemical techniques (Fang *et al.*, 2015)^[11].
- 2. Field vs Laboratory Monitoring:** Residue monitoring can be done directly in the field or under controlled laboratory conditions. Field monitoring helps understand real-time herbicide behavior under natural conditions, while laboratory experiments provide precise data on degradation pathways and residue half-life. Combining both approaches gives a more reliable picture of herbicide persistence (Zhang *et al.*, 2018)^[37].
- 3. Threshold Levels and MRLs (Maximum Residue Limits):** To ensure food and environmental safety, regulatory agencies worldwide have set Maximum Residue Limits (MRLs) for different herbicides in crops and soil. These thresholds help prevent human health risks and trade issues. Regular monitoring of residues ensures that levels remain below internationally accepted standards (FAO/WHO, 2019)^[12].

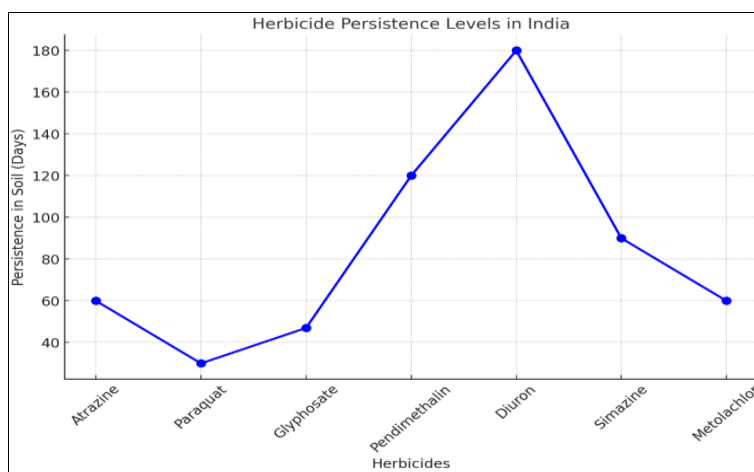


Fig 1: Herbicide Persistence Level in India

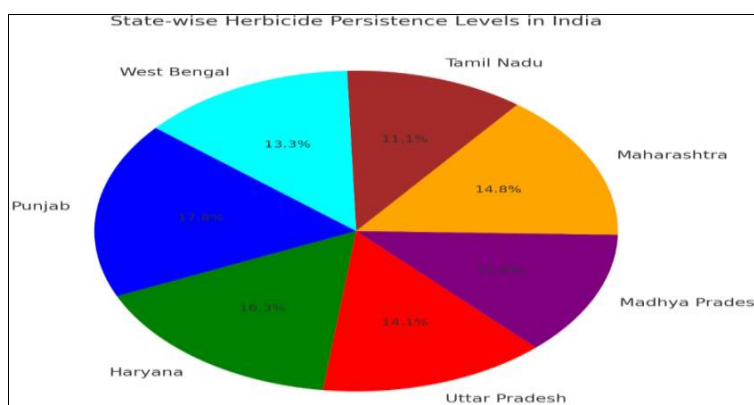


Fig 2: State wise herbicide persistence levels in India

Effects of herbicide persistence

Herbicide persistence refers to the continued presence and biological activity of herbicides in the environment long after their application. The persistence of these chemicals can lead to several ecological, agronomic, and health impacts depending on the soil type, climatic conditions, and chemical nature of the herbicide. One of the major consequences of herbicide persistence is the negative influence on soil health and microbial communities. Studies have shown that residues of herbicides reduce soil microbial biomass and enzyme activity, which are crucial for nutrient cycling and organic matter decomposition. For instance, Amritha (2017) [4] reported that herbicide residues significantly lowered microbial biomass carbon and enzyme activity in tropical soils, thereby affecting soil fertility. Similarly, persistent herbicides can alter the diversity of microbial populations, reducing the abundance of species responsible for degradation and prolonging the herbicide’s half-life (Sayantani Basu & Vasudeva Rao, 2020). Persistence also has serious implications for crop productivity. Residual herbicides in soil may cause phytotoxicity in subsequent crops, leading to stunted root growth, reduced shoot biomass, and poor yield. A study by Debdas Chand (2018) [7] demonstrated that flucetosulfuron persisted longer in soils with low microbial activity and certain pH ranges, which increased the risk of crop injury in rotational systems. Similarly, research on metribuzin

revealed that residues negatively affected the growth of oilseed rape, although the use of organic amendments such as compost or manure accelerated degradation and reduced phytotoxic effects (Mohammad Mehdizadeh, 2019) [24]. Another important effect is the contamination of water bodies through leaching and runoff. Persistent herbicides can move from soil to groundwater or surface water, posing risks to aquatic organisms and potentially contaminating drinking water supplies (Basu& Rao, 2020) [6]. In addition, degradation products of some herbicides can sometimes be more toxic than the parent compound, compounding the risk to ecosystems (Leoci & Ruberti, 2020) [22]. From a broader perspective, herbicide persistence also affects biodiversity and non-target organisms. Long-lasting residues may suppress the growth of beneficial non-weed plants, indirectly reducing food resources for pollinators, insects, and other fauna. Leoci and Ruberti (2020) [22] highlighted that glyphosate residues not only persist in soils but may also affect animal health when exposure is chronic, leading to impacts on organs and reproduction. Overall, herbicide persistence can reduce soil fertility, threaten biodiversity, cause phytotoxicity to subsequent crops, and contaminate water bodies. Effective management practices such as crop rotation, use of organic amendments, and regulatory monitoring are therefore essential to minimize these negative impacts (Basu& Rao, 2020) [6].

Table 2: Effects of Herbicide Persistence on Soil and Plants

Aspect	Effects on Soil	Effects on Plants
Microbial Balance	Reduces beneficial microbes, disrupts soil biodiversity	Weak root development due to lack of symbiotic microbes
Soil Contamination	Accumulates in soil, reducing fertility	Plants absorb toxins, leading to poor growth
Organic Matter Breakdown	Slows decomposition, affects soil aeration	Reduces availability of nutrients from decomposed matter
Soil pH Changes	Alters soil acidity/alkalinity, affecting nutrients	Can lead to nutrient deficiencies or toxicities
Seed Germination	Residual toxicity inhibits seed sprouting	Seeds fail to germinate or show delayed growth
Nutrient Imbalance	Disrupts nutrient cycling in soil	Poor nutrient uptake, leading to stunted growth
Bioaccumulation	Contaminates soil for extended periods	Toxins accumulate in plant tissues, making them unsafe
Environmental Impact	Leaching leads to groundwater contamination	Nearby plants may suffer from unintended herbicide effects

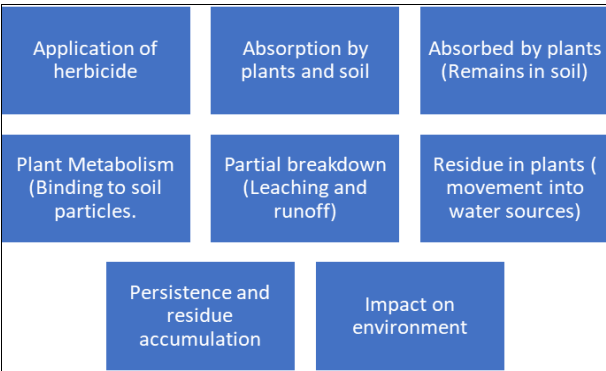


Fig 3: Flow chart how herbicide persist in soil and plants

Herbicide persistence management

1. **Organic Amendments (Compost, Manure, Biochar):** The addition of organic amendments such as compost, farmyard manure, and biochar is one of the most effective strategies to reduce herbicide persistence in soils. These materials increase microbial activity, enhance soil organic carbon, and promote the breakdown of herbicides into non-toxic forms. For example, biochar has been reported to adsorb herbicide molecules, reducing their mobility and leaching potential, while compost and manure stimulate microbial degradation by providing energy sources. Thus, organic amendments improve both soil fertility and residue management simultaneously.

2. **Crop Rotation and Tolerant Crop Selection:** Crop rotation is another practical tool to manage herbicide residues. By alternating crops with different tolerance levels, farmers can minimize the risk of carryover injury to sensitive species. For instance, rotational planting of maize after atrazine application is often safer compared to legumes, which are highly sensitive to atrazine residues. Additionally, selecting herbicide-tolerant crop varieties reduces the risk of crop injury and helps sustain productivity in fields with herbicide persistence problems.
3. **Soil pH and Moisture Management:** Soil conditions play a critical role in herbicide degradation. Managing soil pH and moisture can significantly alter the persistence of certain herbicides. For example, sulfonyleurea herbicides degrade faster in acidic soils through hydrolysis, while they persist longer under alkaline conditions. Similarly, adequate soil moisture enhances microbial activity and accelerates breakdown, whereas dry soils often prolong herbicide residues. Adjusting soil conditions through irrigation, liming, or acidifying amendments can therefore be an effective management strategy (Krutz *et al.*, 2008) [20].
4. **Regulations and Safe-Use Guidelines:** Beyond field-level practices, government regulations and safe-use guidelines are essential to prevent herbicide persistence problems. Regulatory bodies such as FAO, WHO, and national agricultural agencies establish pre-harvest intervals (PHI) and Maximum Residue Limits (MRLs) to ensure food

safety. Extension programs and farmer training on proper dosage, application timing, and safe disposal of containers also play a vital role in reducing long-term residue issues (FAO/WHO, 2019) ^[12]. Compliance with these regulations not only safeguards ecosystems but also prevents trade barriers in international markets.

Recent advances in managing herbicide persistence

- 1. Use of Bioremediation (Microbes that Degrade Herbicides):** Bioremediation is emerging as a sustainable solution to manage herbicide residues in soil and water. Certain bacteria and fungi have natural abilities to use herbicides as a carbon or energy source, leading to their degradation. For example, strains of *Pseudomonas* and *Bacillus* have been shown to degrade atrazine and glyphosate effectively under field conditions. This approach not only reduces persistence but also supports soil health by enhancing microbial diversity (Cycoń *et al.*, 2017) ^[9].
- 2. Nano-Formulations to Reduce Persistence:** Recent developments in nano-formulations of herbicides aim to improve delivery efficiency while minimizing residue problems. Nano-encapsulation allows controlled release of herbicides, ensuring that only small, precise doses are delivered to the target weed. This reduces off-site movement, lowers the risk of leaching into groundwater, and decreases the overall persistence of chemicals in the environment. Moreover, nano-carriers can protect active ingredients from rapid degradation, increasing their effectiveness while reducing application frequency (Kah *et al.*, 2018) ^[18].
- 3. Precision Application Technologies:** Precision agriculture technologies such as drone spraying, GPS-guided applicators, and sensor-based weed detection systems are revolutionizing herbicide use. These tools enable site-specific application, meaning herbicides are applied only where weeds are present rather than across the entire field. This reduces the total quantity of herbicides used, lowers environmental contamination, and helps prevent buildup of residues in soil and water. In addition, data-driven tools allow farmers to monitor herbicide performance and adapt strategies in real time (Shaner, 2014) ^[28].

Case studies

A study by Chand (2018) ^[7] investigated the persistence of flucetosulfuron in soils of Delhi, Karnal, and Kerala. Results showed that soil pH, temperature, and microbial activity strongly influenced degradation. In acidic soils with high microbial activity, degradation was faster, whereas persistence was higher in alkaline soils. This highlights the importance of soil type and environment in managing herbicide residues. In another study, Mohammad Mehdizadeh (2019) ^[24] studied the effect of compost and sheep manure on metribuzin degradation. The results revealed that organic amendments increased microbial activity, reduced the half-life of metribuzin, and minimized phytotoxic effects on subsequent crops like oilseed rape. This shows that organic amendments are an effective management tool for persistent herbicides. Leoci and Ruberti (2020) ^[22] discussed glyphosate's persistence in soils and its indirect effects on animals. They reported that in dry and low-temperature soils, glyphosate degradation was significantly delayed, and long-term exposure caused health issues in animals, including impacts on organs and reproduction. This case highlights the ecological and health risks of persistent herbicides. Amritha (2017) ^[4] analyzed the effect of herbicides

on microbial biomass and enzyme activity in tropical soils. The study revealed that soils with higher microbial activity degraded herbicides faster, whereas low-activity soils retained residues longer. This demonstrates that improving soil health is key in managing herbicide persistence.

Future directions and research needs in herbicide persistence

- 1. Development of Biodegradable Herbicides:** One of the most promising research areas is the design of biodegradable herbicides that break down rapidly after weed control without leaving harmful residues. Advances in green chemistry are helping scientists create molecules that are effective against weeds but environmentally safe, reducing the long-term risks of persistence.
- 2. Genetic Engineering and Microbial Enhancement:** Genetically engineered microbes and plants are being explored to accelerate herbicide degradation in soil. Engineered strains of *Pseudomonas* and *Rhizobium* can metabolize herbicide residues more efficiently than natural strains. Similarly, developing crop varieties with enhanced tolerance and detoxification pathways could help reduce carryover risks (Singh *et al.*, 2018) ^[32].
- 3. Integration of Precision Agriculture and AI:** The future of herbicide management will also rely heavily on artificial intelligence (AI) and machine learning tools. Smart sprayers equipped with cameras and sensors can identify weeds in real time and apply herbicides with high accuracy. AI models can also predict herbicide persistence under different soil and climatic conditions, helping farmers make data-driven decisions.
- 4. Policy and Global Collaboration:** While technological advances are critical, policy frameworks and global collaboration are equally important. International guidelines on herbicide use, stricter monitoring of residues, and investment in farmer education are necessary to minimize risks. Collaborative research networks can speed up the adoption of sustainable practices worldwide (FAO/WHO, 2019) ^[12].

Conclusion

In summary, herbicide resistance is an emerging problem that undermines the efficacy of herbicides and the sustainability of contemporary agriculture. It arises when weeds adapt mechanisms to survive herbicide applications, usually as a result of frequent application of the same herbicide or herbicide group. The implications of herbicide resistance are extensive, including higher management expenses, lower crop yields, and the necessity for more sophisticated weed control measures. Nonetheless, through proactive and comprehensive management techniques, including herbicide rotation, the utilization of two or more modes of action, and integrated weed management (IWM), resistance can be delayed or alleviated. Through diversified control of weeds and enhanced sustainable agricultural practices, we can reduce the effect of herbicide resistance and promote long-term effectiveness in herbicides. Farmers, agronomists, and policy makers need to collaborate to set these measures to ensure the sustenance of herbicide usage's viability and also agricultural production to the future. Overall, herbicide persistence offers opportunities as well as challenges for successful weed management. On the one hand, the long-lasting activity of herbicides offers long-term weed protection. On the other hand, it has the potential to create environmental issues, soil degradation, water pollution, and the emergence of

herbicide resistance. Herbicide persistence must be addressed with a holistic approach, combining strategies like herbicide rotation, modifying application practices, and encouraging soil health by organic matter and microbial processes. Through the use of integrated weed management and precision application technologies, the hazard of herbicide persistence can be reduced. Research into new herbicide formulations, biodegradation processes, and sustainable agriculture practices is necessary to provide effective and environmentally sound weed control in the future.

References

1. Agnihotri A. Herbicide persistence in soil. 2000. Available from: <https://krishikosh.egranth.ac.in/server/api/core/bitstreams/5215a62c-4c7c-4310-bb20-bb8290b57f9c/content>
2. Alferez FM, *et al.* Glyphosate: Its environmental persistence and impact on crop health and nutrition. *Plants*. 2019;8(11):499. <https://doi.org/10.3390/plants8110499>
3. Alletto L, Coquet Y, Benoit P, Heddadj D, Barriuso E. Persistence and sorption of herbicides in soils as affected by soil pH. *Agriculture, Ecosystems & Environment*. 2010;138(1-2):120-127. <https://doi.org/10.1016/j.agee.2010.04.001>
4. Amritha K. Effect of herbicides and soil chemical characteristics on microbial biomass carbon and enzyme activity. *Journal of Tropical Agriculture*. 2017;55(1):114-118.
5. Babal A, Phogat V, Sharma S, Ahlawat IPS. Impact of long-term conservation agriculture induced changes in soil properties on persistence of pendimethalin under different cropping systems. *Soil Research*. 2020;58(7):646-655. <https://doi.org/10.1071/SR20122>
6. Basu S, Vasudeva Rao Y. Environmental effects and management strategies of herbicides. *International Journal of Bio-Resource and Stress Management*. 2020;11(6):518-535. <https://doi.org/10.23910/1.2020.2069d>
7. Chand D. Persistence of flucetosulfuron herbicide as affected by biotic and abiotic factors in Indian soils. New Delhi: ICAR-Indian Agricultural Research Institute; 2018. <http://krishikosh.egranth.ac.in/handle/1/5810093729>
8. Chirukuri R, Atmakuru R. Adsorption and degradation of herbicide halosulfuron-methyl in Indian soils. *Research and Reviews: Journal of Ecology and Environmental Sciences*. 2014;2:40-46.
9. Cycón M, Piotrowska-Seget Z, Kaczyńska A. Microbial strategies for degradation of herbicides in agricultural soils. *Frontiers in Microbiology*. 2017;8:1456. <https://doi.org/10.3389/fmicb.2017.01456>
10. Duke SO. Why have no new herbicide modes of action appeared in recent years? *Pest Management Science*. 2012;68(4):505-512. <https://doi.org/10.1002/ps.2333>
11. Fang H, Yu Y, Zhang H. Advances in analytical methods for herbicide detection in environmental samples. *Trends in Analytical Chemistry*. 2015;67:102-116. <https://doi.org/10.1016/j.trac.2015.01.007>
12. FAO/WHO. Pesticide residues in food – maximum residue limits (MRLs). Joint FAO/WHO Meeting on Pesticide Residues. 2019. <http://www.fao.org/faowho-codexalimentarius/pesticides/jmpr>
13. Furmide GL, Osgerby JM. Persistence of herbicides in soil. *Journal of the Science of Food and Agriculture*. 1967;18:269-273. <https://doi.org/10.1002/jsfa.2740180701>
14. Gilliom RJ. Occurrence of pesticides in U.S. streams and groundwater. *Journal of Environmental Quality*. 2007;36(6):229-248. <https://doi.org/10.2134/jeq2006.0138>
15. Gish TJ, Shirmohammadi A, Wienhold BJ. Herbicide volatilization and leaching in soil-water systems. *Journal of Environmental Quality*. 1995;24(1):146-153. <https://doi.org/10.2134/jeq1995.00472425002400010022x>
16. Greenhalgh R, Dhawan P, Weinberger H. Definition of persistence in pesticide chemistry. *Journal of Agricultural and Food Chemistry*. 1980;28:102-106.
17. Hussain S, Siddique T, Saleem M, Arshad M, Khalid A. Impact of pesticides on soil microbial diversity, enzymes, and biochemical reactions. *Advances in Agronomy*. 2009;102:159-200.
18. Kah M, Kookana RS, Gogos A, Bucheli TD. Nanopesticides: State of knowledge, environmental fate, and exposure modeling. *Critical Reviews in Environmental Science and Technology*. 2018;48(22-24):1825-1867. <https://doi.org/10.1080/10643389.2018.1474535>
19. Kearney PC, Woolson EA, Pilmer JR, Isensec AR. Decontamination of pesticides in soils. *Residue Reviews*. 1969;29:137-149.
20. Krutz LJ, Senseman SA, Sciumbato AS. Factors affecting herbicide degradation in soil. *Weed Science*. 2008;56(2):248-260. <https://doi.org/10.1614/WS-07-098.1>
21. Kudsk P, Streibig JC. Herbicide persistence and photodegradation in agricultural systems. *Pest Management Science*. 2003;59(9):1036-1042. <https://doi.org/10.1002/ps.724>
22. Leoci R, Ruberti M. Glyphosate in agriculture: Environmental persistence and effects on animals. *Journal of Agriculture and Environment for International Development*. 2020;114(1):99-122. <https://doi.org/10.12895/jaeid.20201.1167>
23. Maia AHN, Piveta A, Johnson WG. Residual herbicide in cover cropping systems. *Agriculture*. 2024;14(11):2089. <https://doi.org/10.3390/agriculture14112089>
24. Mehdizadeh M. Impacts of different organic amendments on soil degradation and phytotoxicity of metribuzin. *International Journal of Recycling of Organic Waste in Agriculture*. 2019;8:113-121. <https://doi.org/10.1007/s40093-019-0280-8>
25. OECD. Guidelines for the testing of chemicals: Degradation in soil. Paris: Organisation for Economic Co-operation and Development; 2002.
26. Perreau F. Trace analysis of sulfonylurea herbicides and their metabolites in water using solid-phase extraction and liquid chromatography–tandem mass spectrometry. *Analytical and Bioanalytical Chemistry*. 2007;388:1265-1273. <https://doi.org/10.1007/s00216-007-1326-8>
27. Rose MT, Cavagnaro TR, Scanlan CA, Rose TJ, Vancov T, Kimber S, *et al.* Impact of herbicides on soil biology and function. *Advances in Agronomy*. 2016;136:133-220. <https://doi.org/10.1016/bs.agron.2015.11.005>
28. Shaner DL. Lessons learned from the history of herbicide resistance. *Weed Science*. 2014;62(2):427-431. <https://doi.org/10.1614/WS-D-13-00061.1>
29. Shaner DL, Henry WB. Field history and rotation crop sensitivity to herbicide carryover. *Weed Technology*. 2007;21(3):403-411. <https://doi.org/10.1614/WT-06-124.1>
30. Singh BK. Microbial degradation of herbicides. *Critical Reviews in Microbiology*. 2016;42(2):245-261. <https://doi.org/10.3109/1040841X.2014.929563>
31. Singh BK, Walker A. Microbial degradation of

- organophosphorus compounds. FEMS Microbiology Reviews. 2006;30(3):428-471.
32. Singh S, Kumar V, Gill JPS. Microbial degradation of herbicides: Recent advances and future prospects. International Journal of Current Microbiology and Applied Sciences. 2018;7(2):3430-3442. <https://doi.org/10.20546/ijcmas.2018.702.411>
33. Stork P, Thiele S, Köppen D. Effects of soil moisture on herbicide degradation. Journal of Environmental Quality. 2008;37(2):612-619. <https://doi.org/10.2134/jeq2007.0184>
34. Sumekar W, *et al.* Effect of ametryn herbicide and soil organic matter content on weed growth, herbicide persistence, and yield of sweet corn. Sustainability. 2023;15(23):16238. <https://doi.org/10.3390/su152316238>
35. Walker A, Jurado-Exposito M, Marshall EJP, Ramsey MH. Persistence of herbicides in soil: Laboratory, field and modelling studies. Weed Research. 2001;41(4):229-247. <https://doi.org/10.1046/j.1365-3180.2001.00233.x>
36. Wauchope RD, Yeh S, Linders J, Kloskowski R, Tanaka K, Rubin B, *et al.* Pesticide soil sorption parameters: Theory, measurement, uses, limitations and reliability. Pest Management Science. 2002;58(5):419-445. <https://doi.org/10.1002/ps.489>
37. Zhang C, Liu X, Dong F. Monitoring of pesticide residues in agricultural soils and crops: Field and laboratory approaches. Environmental Pollution. 2018;243:1310-1318. <https://doi.org/10.1016/j.envpol.2018.09.032>