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Review Article

Herbicide Impacts on Weed Dynamics and Soil Microbial Communities in Rice Fields: Challenges and Opportunities for Sustainable Rice Production

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ABSTRACT

Rice is an important staple crop, and its productivity can be severely affected by weed infestations, resulting in greater yield loss. In direct-seeded rice (DSR) systems, herbicides have been successfully used to control weeds, but issues with herbicide resistance and their effects on soil microorganisms persist. The purpose of the present study is to assess the effects of herbicides on rice ecosystems and to synthesise our knowledge of weed populations, soil microbial communities, and crop production. The results showed that herbicides are effective at suppressing major rice weeds, including *Echinochloa crus-galli, Cyperus difformis,* and *Monochoria vaginalis*, thereby reducing weed biomass and increasing rice yields. If used repeatedly or heavily, microbial abundances might be affected, and beneficial groups such as nitrogen-fixing bacteria and arbuscular mycorrhizal fungi (AMF) may be less active. These effects might threaten soil health and the sustainability of rice production. The review also emphasises the need to use integrated weed management (IWM) strategies that combine

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herbicides with non-chemical methods and bioremediation to mitigate long-term ecological damage. Future studies should focus on optimising herbicide use and developing herbicide-resistant rice cultivars to improve rice production systems.

Keywords: Herbicide, rice, soil microbes, weed dynamics, yield

INTRODUCTION

Rice (*Oryza sativa* L.) is the second most produced cereal crop in the world, and over half of the world's population depends on it as a staple food (Zainuddin et al., 2021). For an estimated 3.5 billion people worldwide, rice is their main food source, particularly in Asia, where it contributes up to 50% of total dietary energy (Li et al., 2018). Beyond its role in food security, rice cultivation contributes greatly to rural livelihoods, economic development, and ecosystem stability (Meher et al., 2024). In order to meet future food demand, rice production is going to rise, especially in the upcoming decades, due to the world's population growth (Mohidem et al., 2022).

Despite its importance, rice productivity is severely constrained by several biotic factors, among which weed infestation is one of the most significant. Weeds compete with rice plants for light, nutrients, water, and space, potentially causing yield losses up to 50%-100% in direct-seeded rice (DSR) systems (Rodenburg et al., 2022). *Echinochloa* spp., *Cyperus* spp., *Leptochloa chinensis*, and *Oryza sativa f. spontanea* (weedy rice) are repeatedly identified as the most problematic due to their high competitiveness and adaptability to rice field conditions (Butts et al., 2022; Calha et al., 2022). Weeds exhibit strong adaptive capacity to different management practices, increasing the complexity of control strategies (Kumar, Choudhary, et al., 2022). In order to achieve the highest possible output in paddy fields, it is essential to take measures to control weed infestation (Ramli et al., 2024).

Herbicide use has been extensively proven as a successful strategy for reducing weed competition and enhancing crop performance (Olajumoke et al., 2016). Depending on when they are applied and how plants absorb them, herbicides can be broadly categorised into pre-emergence and post-emergence forms (Krähmer et al., 2021). In particular, post-emergence herbicides are extensively used in rice systems due to their ability to target weeds after they have emerged, thereby allowing more precise weed control (Sen et al., 2021).

However, the usage of herbicides to control weeds is increasing, which has raised several concerns related to their sustainability and long-term effectiveness (Wang et al., 2021). Inadequate application rates and the repeated use of the same herbicide can result in the development of herbicide-resistant weed populations, crop phytotoxicity, and reduced efficacy (Jin et al., 2022). In addition, excessive herbicide use can cause environmental

pollution and harm non-target organisms, such as beneficial soil microorganisms (Hakim et al., 2021).

Soil microbes are critical for soil health and plant growth. They cycle nutrients through the soil, clean up organic debris and treat diseases (Bhardwaj et al., 2024). Herbicide use can disrupt microbial populations and affect soil biochemical processes and the overall ecosystem (Xiong et al., 2021).

While recent reviews have examined sustainable weed management in rice (cultural, mechanical, biological, and chemical), there has been less focus on the ecology of weed control strategies that sustain crop production without long-term environmental impacts. Understanding these interactions is crucial for developing effective weed control methods that contribute to crop yields and minimise environmental impact. The review aims to provide an in-depth understanding of herbicide interactions in rice ecosystems, weed behaviour, resistance issues, impact on soil microbes and rice yields and sustainable recovery strategies.

METHODOLOGY

The review described the development and challenges in rice weed control, herbicide use, soil microbiology and crop biotechnology in recent years. The literature was searched through several major academic databases, e.g., Scopus, Web of Science, ScienceDirect and Google Scholar. The search terms were generated by incorporating keywords related to rice production, weed control, herbicide effectiveness, microbial interactions, soil ecology and biotechnological progress. Although older papers were also included for historical context, we mainly searched for recent papers published between 2019 and 2025. The retrieved articles were then analysed to determine their relevance for the purpose of the review.

HERBICIDE AND WEEDS IN RICE FIELD ECOSYSTEM

Impact of Herbicides on Weed Management

Post-emergence herbicides have proven highly effective at suppressing weeds in rice fields. Field trials in direct-seeded rice (DSR) systems have demonstrated that most post-emergence herbicides can reduce weed biomass by 60-90% within weeks of application (Jehangir et al., 2024). As shown in Figure 1, herbicide application interacts with various factors in the rice ecosystem, influencing both weed control and soil health. However, in DSR systems, the use of a single pre- or post-emergence herbicide often fails to control the broad spectrum of weeds present. As a result, tank mixtures or sequential applications of herbicides are commonly required (Kumar, Chhokar, et al., 2022).

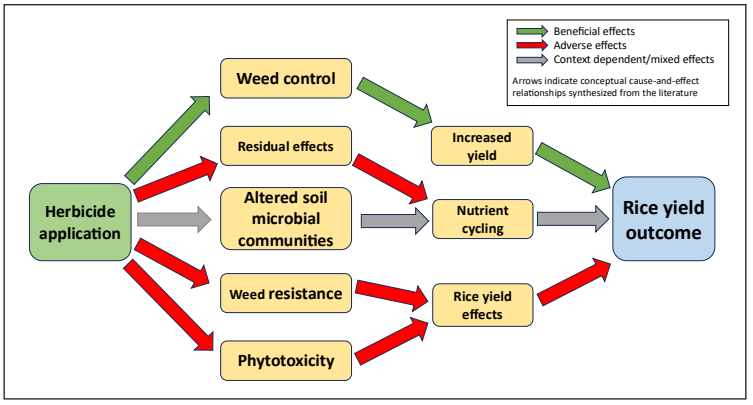


Figure 1. Herbicide effects on weed management, soil health, and rice yield

One innovative approach gaining traction in sustainable agriculture is Integrated Weed Management (IWM), which combines chemical and non-chemical control methods, including bioherbicides, to manage weed populations effectively (Kamala Bai et al., 2025). Given that rice fields in Asia host over 40 weed species (major weeds list shown in Table 1), selecting herbicides with diverse modes of action is essential for effective control (Chen et al., 2023). For example, Almix 20% WP has been shown to effectively control all types of weed populations in rice fields (Dey et al., 2020). While wet DSR faces challenges from diverse weed species, broad-spectrum herbicide mixtures can help mitigate issues such as weed shifts and herbicide resistance (Meher et al., 2024).

Table 1
Major weeds in rice fields in Asia (International Rice Research Institute [IRRI], 2025)

Weed Category	Scientific Name	Common Family Name
Grass	*Digitaria setigera*	Poaceae
	Digitaria ciliaris	Poaceae
	Echinochloa colona	Poaceae
	Echinochloa crus-galli	Poaceae
	Echinochloa glabrescens	Poaceae
	Eleusine indica	Poaceae
	Ischaemum rugosum	Poaceae
	Leptochloa chinensis	Poaceae
	Oryza sativa (weedy rice)	Poaceae
	Paspalum distichum	Poaceae
Sedge	*Cyperus iria*	Cyperaceae
	Cyperus difformis	Cyperaceae
	Cyperus rotundus	Cyperaceae
	Fimbristylis miliacea	Cyperaceae

Table 1 (*continued*)

Weed Category	Scientific Name	Common Family Name
Broadleaf	*Commelina benghalensis*	Commelinaceae
	Eclipta prostrata	Asteraceae
	Ipomoea aquatica	Convolvulaceae
	Ludwigia octovalvis	Onagraceae
	Ludwigia adscendens	Onagraceae
	Monochoria vaginalis	Pontederiaceae
	Sphenoclea zeylanica	Sphenocleaceae

The use of early post-emergence treatments, such as triafamone and ethoxysulfuron, has achieved 87-90% weed control efficacy while maintaining seed yields comparable to those in weed-free conditions, as demonstrated in two-year field trials (Jehangir et al., 2024). Additionally, Mathew et al. (2025) reported that the pre-emergence application of pretilachlor combined with pyrazosulfuron ethyl efficiently managed grasses, sedges, and broadleaf weeds, especially at 20 days after sowing (DAS). Furthermore, the application of Acetochlor, S-metolachlor, pyroxasulfone, dimethenamid-P, and pethoxamid, applied in fall, has been successful in controlling weedy rice in subsequent rice crops by more than 90% (Bertucci et al., 2019). Low doses of bispyribac sodium (20-40 g/ha) effectively controlled mixed weed flora, especially *Echinochloa* spp., *Cyperus difformis*, and *Monochoria vaginalis*, which lowered labour needs and weed management expenses (Ahmed et al., 2021).

Herbicide combinations, such as fenoxaprop-p ethyl 6.7% EC (w/w) + ethoxysulfuron 15% WDG (w/w) (50+15) g/ha, offer an effective solution for improved weed management and higher grain yield (Meher et al., 2024). However, some herbicide tank mixtures exhibit antagonistic interactions, as observed when quizalofop was mixed with other herbicides against various grass weed combinations (Lancaster et al., 2019). Herbicide tank mixtures can undergo three types of interactions: additive, synergistic, or antagonistic. Approximately 97% of farmers employ herbicide mixtures to reduce operational costs, labour hours, and machine entries (Barbieri et al., 2022).

Hakim et al. (2021) found that applying herbicides at higher than recommended doses, such as pretilachlor, propanil + thiobencarb, bensulfuron + MCPA, and pretilachlor, remains effective for both weed control and maintaining grain yield under salinity conditions. In addition to chemical control, non-chemical weed management tactics, such as hoeing at 12 DAS followed by Sesbania co-culture or rice straw mulching at 4-6 t ha^{-1}, demonstrated effective weed suppression in direct-seeded rice (Nagargade et al., 2024). Table 2 lists commonly used herbicides for weed control in rice cultivation.

Table 2
Herbicides commonly used in rice cultivation (Bakar, 2004; Mispan et al., 2019; Rajput et al., 2020)

S.N.	Common Name	Trade Name	Dose (g/ha)	Stages of Application / Salient Features
		Pre-Emergence Herbicide:		
1	Benthiocarb	Bolero	3400-4500	4-10 days after seeding (DAS). Flooding should be done 3-5 days after treatment.
2	Pendimethalin 30 EC	Stomp, Pendisar	1000-1500	0-3 DAS —annual grasses and some broadleaf weeds can be controlled.
3	Fluazfop_P	Fusilade	105-250	Applied before tillage at the 2-4-leaf stage of weedy rice.
4	Anilofos 30EC	Arozin, Anilogard	400	3-5 DAS —many annual grasses and some broadleaf weeds can be controlled.
5	Pretilachlor 30.7% EW	Sofit, Rift, Erage-N	550-700	0-3 DAS — for effective weed control, soil moisture must be wet for a few days.
		Post-Emergence and Mixture of Herbicides:		
1	Fenoxaprop-p-ethyl 6.7EC	Rice Star	57-61	25-30 DAS —Should be applied with all pre-emergence herbicides. Excellent control of annual grasses.
2	Bispyribac-sodium 10SC	Nominee Gold, Adora	20	15-20 DAS — Controls annual grasses, some broadleaf weeds and sedges.
3	Propanil	Stam, Tawan	2000-4000	Controls weeds and annual grass; has low soil persistence.
4	Chlorimuron-ethyl + Metsulfuron-methyl 20 WP	Almix	4	15-20 DAS —annual broadleaf weeds and grasses can be controlled
	Quinclorac	Qunstar, Rumpas M	250	Superior control of barnyard grass.
5	Molinate + Bensulfuron	Londax	3.0 + 0.03 kg a.i./ha	6-10 DAS — Wide spectrum of weed control under standing water conditions.
6	Bispyribac-sodium 10SC + Almix	Adora + Almix	20 g + 4 g a.i./ha	20 DAS — Kills all types of weeds.
7	Pretilachlor 30.7% EW + Bispyribac-sodium 10SC	Nominee Gold + Sofit	600 + 20	1-3 and 20 DAS — Pre- and post-emergence herbicides, which give the best results.

Integrated weed management (IWM) strategies that combine crop rotation, herbicide rotation with different modes of action, proper timing, and economic combinations help to disrupt weed life cycles and provide effective management (Kaur et al., 2023). In addition, the development of herbicide-resistant rice types through CRISPR-Cas-mediated gene editing and genomic transformation has been identified as a promising approach to managing weed populations (Luo & Liu, 2025).

Herbicide Resistance Development in Weeds

Rice productivity, despite its global importance, is severely constrained by weed pressure, widely recognised as a major biotic stress (Rahaman et al., 2021). The heavy reliance on herbicides has led to the emergence of herbicide-resistant weed populations, which in turn reduce rice yields and increase production costs (Onwona-Kwakye et al., 2020). Herbicide resistance has been reported in 37 distinct cases, involving 30 active herbicide components and 17 different weed species (Casimero et al., 2022). Resistance to commonly used herbicides, such as quinclorac, penoxsulam, and metamifop, has become increasingly prevalent (Wang et al., 2021). Barnyard grass, a major weed species, has also developed resistance to propanil (photosystem-II inhibitor), with 85 of 116 resistance cases reported between 1986 and 2022 (Damalas & Koutroubas, 2023).

Integrated herbicide resistance management strategies, such as crop rotation, herbicide rotation with different modes of action, the use of residual herbicides, proper timing of applications, and combining chemical control, are essential for managing this growing problem (Kumar et al., 2023). Advances in genetic modification, such as CRISPR-Cas9, have enabled the development of herbicide-resistant rice varieties. For example, a study demonstrated the creation of herbicide-tolerant Basmati rice using homology-directed repair of the OsALS gene, conferring resistance to bispyribac-sodium and chlorsulfuron while maintaining normal plant phenotype and yield (Zafar et al., 2020).

Development of Herbicide-Tolerant Rice

In rice fields, most herbicides that control weeds often harm the rice crop itself. Therefore, herbicide-resistant rice varieties are being developed to alleviate the weed problem (Jin et al., 2022). Transgenic techniques have been used to produce glyphosate- and glufosinate-resistant rice, although their safety remains a limiting factor for commercial use (Luo & Liu, 2025). Additionally, CRISPR/Cas9 technology has shown promise in modifying rice endogenous genes to create herbicide-resistant rice (Liu et al., 2020). Figure 2 shows the techniques involved in developing herbicide-resistant rice.

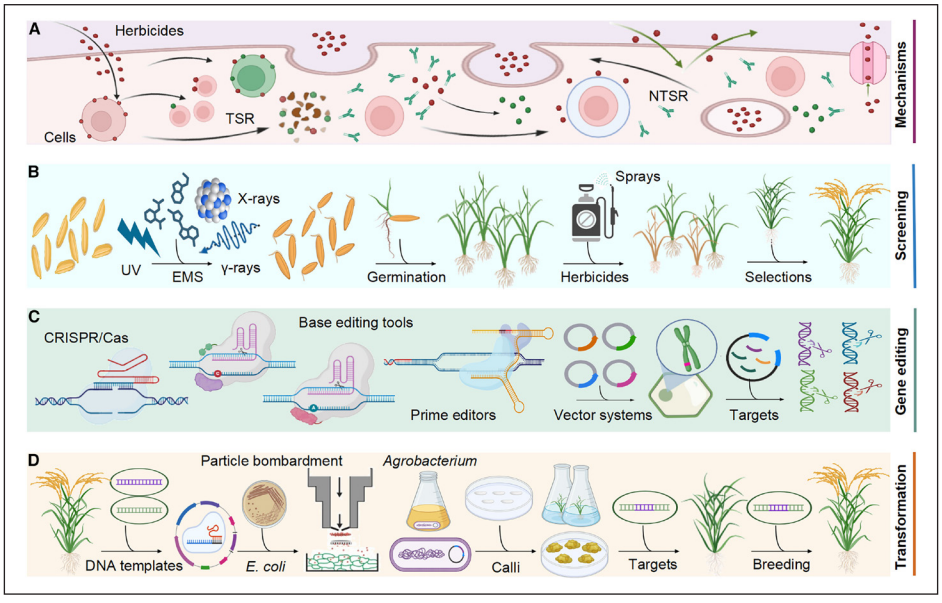


Figure 2. Graphical illustrations of the techniques applied in developing herbicide-resistant rice (Luo & Liu, 2025); (A) Rice cells resist herbicides through two main mechanisms: target-site resistance (TSR; conferred by mutations or overexpression of target proteins) and non-target-site resistance (NTSR; involving herbicide sequestration, detoxification, translocation via metabolic degradation, or reduced penetration); (B) Screening herbicide-resistant rice mutants created by chemical or irradiation, followed by herbicide treatment provides selection pressure; (C) Herbicide-resistant rice breeding using gene knockout, base editing, and prime editing; (D) Particle bombardment and Agrobacterium-mediated transgene transfer are the main herbicide-resistant rice breeding technologies

HERBICIDE AND SOIL MICROORGANISM

Impact of Herbicides on Soil Microbes

The growing global population and demand for food have increased herbicide use, raising environmental concerns and harming beneficial soil microorganisms (Shultana et al., 2025). The application of herbicides can greatly alter soil microbial communities, frequently resulting in a decrease in microbial abundance within 7 to 30 days post-treatment (Kremer & Means, 2009). The intensity of these impacts varies with soil attributes, including texture, tillage practices, organic matter content, and the chemical properties of the herbicides used (Yadav et al., 2017).

Studies on herbicides provided more insight into how they affect soil microorganisms. For instance, applying bispyribac sodium led to a considerable decrease in soil enzyme activity and microbial biomass carbon (MBC), even at the recommended dose (35 g/ha) and double dose (70 g/ha) (Kumar et al., 2020). On the other hand, it was found that the more recent herbicide tripyrasulfone, which contains an HPPD inhibitor, only temporarily affected soil enzyme activity in rice fields and posed no long-term risk to the soil's overall health (Sun et al., 2024).

Mixtures of herbicides such as atrazine, nicosulfuron and mesotrione have been shown to alter the composition of soil microbial communities. These mixtures tend to favor the increase of herbicide-tolerant taxa and the suppression of herbicide-sensitive species (Ma et al., 2025). In some cases, strategies combining herbicide use and water management (e.g. preventing seed dispersal by water) have been found to contribute to the conservation of beneficial microorganisms, including AMF (Li et al., 2025).

Inorganic pesticides and herbicides can affect AMF, which are important for plant nutrient uptake, in both positive and negative ways. These fungi absorb active chemicals from the rhizosphere either through plant roots or fungal hyphae (Hage-Ahmed et al., 2019). Herbicide mixtures can greatly reduce the abundance of beneficial microbes, such as *Bacillus,* but enrich for other species, such as *Penicillium*, as shown in research (Ma et al., 2025). Also, some herbicides, such as fomesafen, have been shown to affect the microbial interactions in the rhizospheres of legumes, greatly reducing the activity of the nifH gene, which is known to be related to nitrogen fixation (Chen et al., 2025).

In direct wet-seeded (DWS) rice systems, herbicide application initially reduces the populations of soil bacteria, fungi, and actinomycetes. Still, these microbes can bounce back 55 days after sowing, and therefore, herbicide toxicity diminishes over time (Mathew et al., 2023). This ability to degrade herbicides means that microorganisms can also serve as bioindicators of soil health, offering insights into changes within the soil ecosystem after herbicide application (Milošević & Govedarica, 2002).

A notable concern is that glyphosate-based herbicides significantly decrease AMF spore and vesicle biomass, as well as overall mycorrhizal colonisation of roots (Zaller et al., 2014). Despite these negative effects, bioremediation has been proposed as a potential solution to address herbicide residues in soil. This microbial approach can aid in herbicide degradation, although its effectiveness may be limited by the risk of producing toxic metabolites during the degradation process (Pileggi et al., 2020). Figure 3 shows the soil environment as a container, showing where each type of microbe lives, how herbicides affect them, and where bioremediation steps in.

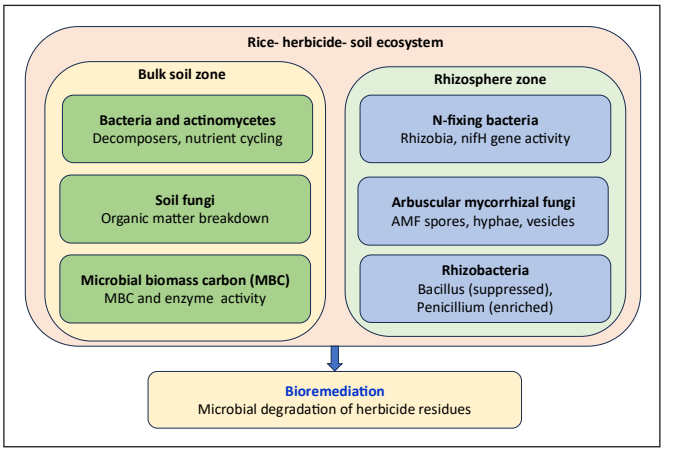


Figure 3. Herbicide impacts on soil microbial communities and bioremediation. Arrows represent conceptual cause-and-effect relationships and interactions synthesised from existing literature

HERBICIDE AND RICE YIELD

Weed competition can remarkably reduce rice yields, with potential losses reaching up to 80% in the absence of effective weed management strategies (Kraus & Stout, 2019). Pre-emergence herbicides have been shown to increase grain yields by 16-15% across consecutive cropping seasons, particularly when combined with high fertiliser rates, optimal seed drills (80 kg ha^{-1}), and improved canopy growth uniformly in direct-seeded rice systems (Liao et al., 2021). However, not all herbicides are equally effective. Research shows that pendimethalin at 2 kg ha^{-1} reduced rice plant SPAD values (a measure of chlorophyll content) by 100%, leading to severe phytotoxicity. In contrast, pretilachlor with safener showed minimal phytotoxicity and did not affect rice biomass (Motmainna et al., 2025).

Certain herbicides have demonstrated substantial yield improvements. For example, applying Almix 20% WP at 4g a.i. ha^{-1} increased rice yields around 59.1% compared to the untreated control (Dey et al., 2020). Herbicide mixtures such as Pretilachlor followed by Bentazon/MCPA, or Bispyribac-sodium followed by Bentazon/MCPA, showed enhanced weed control efficacy and increased rice grain yields, resulting in better economic returns (Abdullah et al., 2023). Interestingly, hand weeding also proved highly effective, with a yield of 5.50 t ha^{-1}, comparable to the combination of bensulfuron-methyl + pretilachlor (5.39 t ha^{-1}) and triafamone + ethoxysulfuron (5.29 t ha^{-1}) (Nagarjun et al., 2025).

Some herbicide combinations are more suited for specific growth stages. For example, Pretilachlor + pyrazosulfuron ethyl was most effective for early weed control, while pendimethalin followed by triafamone + ethoxysulfuron was ideal for managing late-season weed pressure and maximising rice yields (Mathew et al., 2025). Another study shows that the application of imidazoline herbicide 28 days before planting can result in a 10 % reduction in plant height or grain production in non-tolerant rice (Chiapinotto et al., 2024). Additionally, a study revealed that mechanised conoweedings coupled with the pre-emergence application of bensulfuron methyl + pretilachlor (60 and 600 g a.i. ha^{-1}) and post-emergence treatment with 2,4-D (0.75 kg a.i. ha^{-1}) resulted in improved crop growth and enhanced yields (Mir et al., 2024). In trials, the pre-mix triafamone + ethoxysulfuron proved most effective against grasses and sedges, achieving a remarkable 383% increase in yield, reaching 7.3 t ha^{-1} compared to the weedy check (Jehangir et al., 2024). The conceptual framework summarising the interactions of herbicides and rice yield is presented in Figure 4.

Herbicides like oxadiazon also demonstrated substantial benefits, boosting rice grain yield by 61% (4.6 t/ha) compared with untreated controls. This highlights the importance of selecting herbicides based on soil moisture regimes to optimise yield (Onwuchekwa-Henry et al., 2023).

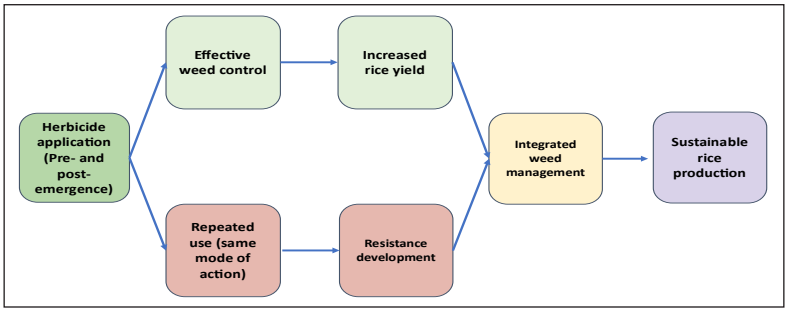


Figure 4. Herbicide effects on weed management and rice sustainability. Arrows indicate conceptual cause-and-effect relationships synthesised from the literature

RESIDUAL EFFECT OF HERBICIDE

Herbicides can increase crop yields but may also cause long-term issues if overapplied in soil, leading to phytotoxicity and herbicide residues that can contaminate groundwater and pose food safety risks (Sondhia & Singh, 2018). Herbicides may remain in the soil longer with different application methods. Banded applications that target smaller areas use less herbicide and thus are less likely to be associated with residual effects than broadcast applications (Curran, 2016).

In water-seeded rice, pendimethalin application after emergence (as a byproduct of or in combination with other herbicides) can provide residual soil activity to control late-emerging grasses (Becerra-Alvarez & Al-Khatib, 2025). Bommayasamy and Chinnamuthu (2024) also found that the residual effects of oxadiargyl-loaded zeolite from rice cultivation have been beneficial in reducing weeds and increasing crop growth, yield, and nutritional quality in the following crops, such as okra.

Heavy rainfall or irrigation can induce herbicide runoff, whereas high temperatures exacerbate the breakdown of herbicide residues through chemical and microbiological processes (Norsworthy et al., 2024). Fomesafen has been widely used in legume crop soils, leading to high residue buildup in the rhizosphere and, therefore, negatively impacting nitrogen-fixing microbial communities in the soil (Chen et al., 2025).

Soil microbes are affected by residual herbicides when residues exceed 310 µg/kg, compared with soils with lower residuals (Wang et al., 2024). Residual herbicides may influence the processes of soil ecology, for example, sulfur oxidation and phosphorus absorption, which are essential to soil health and plant growth (Cao et al., 2023). Herbicide residues may even encourage microbes to break them down, forming an ecological community, and thus microbes may adapt to these residues (Ruuskanen et al., 2023).

Low residual herbicide levels can increase the relative abundance of microorganisms that benefit soil processes, thereby increasing soil multifunctionality (Gao et al., 2024). Herbicides like atrazine and acetochlor significantly decrease the presence of essential

microbial groups such as actinobacteria, proteobacteria and acidobacteria, which play a fundamental role in nutrient cycling (Zhang et al., 2023).

The chemical properties of a herbicide, its environmental conditions in soil, and its half-life are factors that affect its persistence, especially for soil applications. Table 3 shows the half-lives of some common herbicides in soil that farmers and agronomists need to understand to manage residual impacts.

Table 3
Some herbicides half-lives in soil (Sondhia, 2016)

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

RECOVERY STRATEGIES FOR HERBICIDE EFFECTS AND SUSTAINABLE AGRICULTURE

The demand for chemical herbicides is steadily increasing due to their proven effectiveness in controlling weed growth and maximising crop productivity (Al-Samarai et al., 2018). However, herbicide persistence in agricultural environments can cause long-term ecological and soil health issues, making herbicide removal solutions essential for sustainable agriculture (Hassaan & El Nemr, 2020). The effects of herbicide application on weed control, crop yield, and soil biological properties reported in previous studies are summarised in Table 4.

Table 4
Herbicide effects on weed control efficiency, crop yield, and soil microbial responses

Herbicide Treatment & Dose	Weed Control Efficacy	Yield Response	Soil Microbial & Enzyme Response	Study Location	References
Almix 20% WP (Chlorimuron-ethyl + Metsulfuron-methyl) @ 4 g a.i./ha	Effective broad-spectrum weed suppression	59.1% yield increase compared to the untreated control	Minor temporary residue effect on soil microbes	India	Dey et al. (2020)
Bensulfuron-methyl + Pretilachlor OR Triafamone + Ethoxysulfuron	High weed control efficacy	Yields of 5.39 t/ha & 5.29 t/ha, comparable to Hand Weeding (5.50 t/ha)	Minimal effects on soil microflora and nutrient dynamics	India	Nagarjun et al. (2025)
Bispyribac-sodium (post-emergence) @ recommended (35 g/ha) & double (70 g/ha) dose	High post-emergence control of grass, sedge, and broadleaf weeds	Not measured	decrease in soil enzyme activities and MBC	India	Kumar et al. (2020)
Sequential Pre- and Post-emergence herbicide applications	Continuous weed suppression throughout the vegetative phase	High compatibility with crop yield potential	Initial population suppression of bacteria, fungi, and actinomycetes; recovery by 55 DAS	India	Mathew et al. (2023)
Triafamone + Ethoxysulfuron (early post-emergence)	87.0% - 90.0% control; 60.0% - 90.0% biomass reduction	383.0% yield increase (7.3 t/ha) vs. untreated check	Not explicitly evaluated	India	Jehangir et al. (2024)
Tripyrasulfone (QYR301, HPPD-inhibitor post-emergence)	High selective control	Safe for rice crop; preserves yield potential	Rapid soil dissipation (half-life 4.3-8.0 d); temporarily stimulates urease/phosphatase	China	Wang et al. (2019)
Oxadiazon (pre-emergence)	High pre-emergence control depending on soil moisture	61.0% yield increase (4.6 t/ha) compared to the untreated control	Not measured	Cambodia	Onwuchekwa-Henry et al. (2023)
Fomesafen (post-emergence residues)	General broadleaf control	Not measured	Negatively impacts nitrogen-fixing communities; heavily reduces nifH abundance	China	Chen et al. (2025)

The studies presented in Table 4 show that the use of herbicides typically results in better weed control and higher crop yields. Although some compounds have only a small impact on soil microbial characteristics, others might temporarily reduce microbial numbers or alter specific functional microbial communities. Therefore, recovery strategies should focus not only on herbicide removal but also on restoring soil biological functions.

Among the available approaches, microbial-based remediation and nanotechnology-assisted degradation have gained attention for their potential to reduce herbicide residues and restore soil health. Herbicide degradation may be enhanced by TiO_2 and ZnO nanomaterials. These nanomaterials protect microbial degraders and promote microbe-herbicide interactions (Sunanda & Ghosh Sachan, 2023). Pseudomonas and Acinetobacter strains can degrade hydrocarbons at 72-96%. These bacteria are also resistant to 2,4-D, imazethapyr, and tribenuron-methyl, making them promising bioremediation candidates for soil herbicide pollution (Korshunova et al., 2024). Apart from microbial-based methods, plant-derived chemicals have emerged as potential long-term alternatives to synthetic herbicides.

Allelochemicals produced by allelopathic plants are a more environmentally friendly weed management method. This is something that could be used for the greenhouse effect (Rahaman et al., 2022). And herbicides developed from natural compounds are relatively cheaper and more eco-friendly than manufactured ones (Bashar et al., 2023). Plant-based alternatives, such as Nerium and Olive extracts, are also promising for weed control, as well as to meet the increasing demand for sustainable agriculture and herbicide-free agriculture, while keeping herbicide use low (Al-Samarai et al., 2018). These solutions will prevent the use of herbicides and help address the mounting demand for sustainable farming practices.

In metabolic modelling (Figure 5), further developments contribute to the development of more efficient recovery strategies. By simulating the metabolic capabilities of microbial herbicide degraders, researchers can design more effective bioremediation methods that target herbicide toxicity. This approach enhances the ability to reduce herbicide residues in soil, fostering long-term agricultural sustainability (Dhakar et al., 2022).

Climate change may affect herbicide persistence, degradation, and efficacy by altering temperature, precipitation, soil moisture, and microbial activity. Therefore, future herbicide management strategies should incorporate climate-adaptive approaches to ensure effective and sustainable weed control (Zhang et al., 2023).

In addition to biological and technological approaches, regulatory frameworks are crucial to promoting sustainable herbicide management. Regulatory agencies, such as the United States Environmental Protection Agency (EPA), assess herbicides for environmental fate, toxicity, and ecological risks before approval and may impose restrictions on their use to minimise adverse impacts (U.S. Environmental Protection Agency, 2024). Similarly, the European Union Regulation (EC) No. 1107/2009 and the Sustainable Use of Pesticides

Directive 2009/128/EC emphasise precautionary assessment, reduced pesticide dependence, and the adoption of integrated pest management practices (European Parliament and Council of the European Union, 2009). Therefore, integrating recovery strategies, climate-adaptive approaches, and regulatory policies is essential to achieving long-term sustainability in rice production systems.

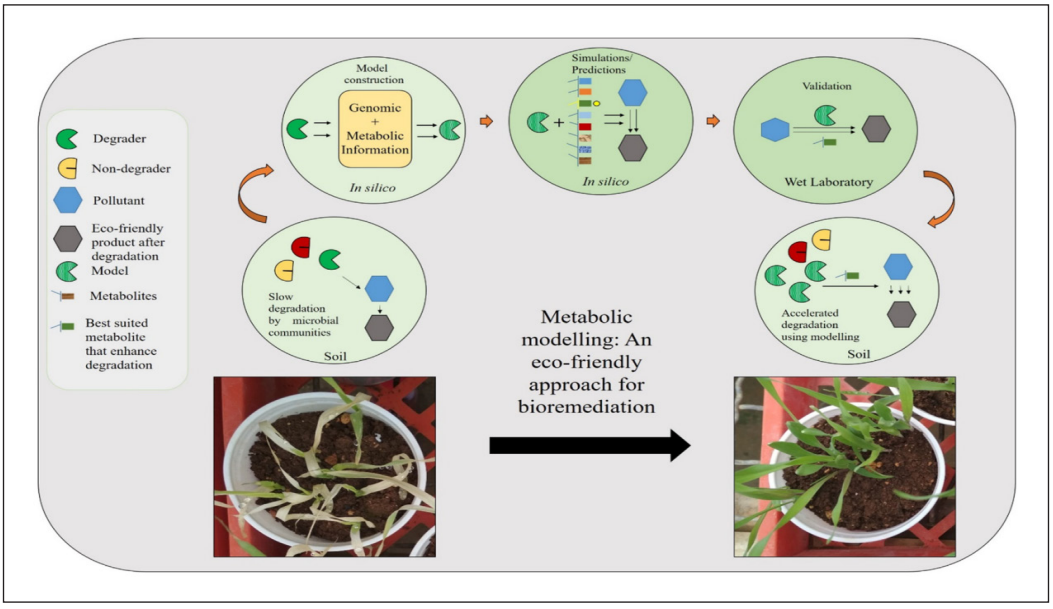


Figure 5. An overview of the various stages involved in the metabolic modelling approach for bioremediation (Dhakar et al., 2022)

CONCLUSION

Several studies have shown that herbicides can reduce the abundance of micro-organisms, harm nitrogen-fixing bacteria, prevent AMF from colonising the soil, and disrupt soil enzyme activity. Although herbicides are effective at weed control, with an efficacy rate of 85 to 95 percent, which results in higher crop yields, they also cause considerable problems. As the half-lives of herbicides range from a few days to several months, there are concerns about their residual effects on delicate crops and on soil biological activity. Dependence on herbicides can be reduced by using bioremediation, organic amendments, and precise application methods. The development of herbicide-resistant rice varieties through advanced breeding represents a promising strategy for selectively controlling weeds. Future research should focus on long-term ecological monitoring, soil health indicators, herbicide-resistant rice, and the use of low-risk herbicides. These measures will make herbicide use more efficient, thereby contributing to more sustainable farming practices.

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