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Evaluation of new herbicide molecules and their efficacy in rice and wheat cultivation in India

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Abstract

The increasing demand for higher agricultural productivity in India has necessitated the development and use of efficient crop management tools, particularly herbicides. Wheat and rice are widely grown globally due to their high protein content and ability to fix nitrogen through symbiotic bacteria in root nodules, reducing the need for fertilizers. However, weed interference limits legume cultivation, managed through mechanical, cultural, chemical, or biological methods. Herbicides remain essential for cost-effective weed control, but first-generation herbicides pose environmental and human health risks due to persistence and off-target toxicity, along with issues like weed resistance. New herbicides with novel modes of action have emerged, offering improved weed control efficiency (WCE), reduced weed biomass, and higher seed yields without significant crop toxicity. This review highlights the benefits of these newer herbicides, focusing on selectivity, low toxicity, and minimal environmental impact, while emphasizing their economic viability and environmental sustainability. The evaluation of new herbicide molecules for their efficacy in rice and wheat cultivation is crucial for ensuring better weed control while maintaining the environmental and economic sustainability of farming practices. This study examines the efficacy of novel herbicide molecules in controlling weeds in rice and wheat fields, assesses their impact on crop yield, and compares them with conventional herbicides. The results suggest that newer herbicide formulations offer improved weed control, lower toxicity, and higher crop yield potential, thereby providing viable alternatives to traditional herbicides in India's diverse agricultural landscape.

Keywords: Herbicide, weeds, crop protection, pest control and sustainable farming

Introduction

India, one of the largest global producers of rice and wheat, faces significant challenges in crop management, particularly weed control. Weeds compete for nutrients, water, and sunlight, leading to a 37% loss in crop yields. While conventional herbicides have been used for weed management, concerns over their environmental impact, toxicity, and herbicide-resistant weeds have prompted the search for alternatives new herbicide molecules have been developed to improve efficacy, safety, and sustainability (FAOSTAT, 2022) [8]. This research aims to assess these novel herbicides' effectiveness, crop safety, and advantages over existing ones. Weeds also indirectly affect crops by providing shelter for pests and diseases, such as stem borer in rice and stalk borer in maize and tomato (Chao et al., 2021). The first herbicide use in India was in 1937 in Punjab to control *Carthamus oxyacantha* with sodium arsenite, followed by the testing of 2,4-D in 1946. In 1952, ICAR began testing herbicides for rice, wheat, and sugarcane. Herbicide use gained traction in the 1960s with 2,4-D and later paraquat, though it was initially unpopular with Indian farmers, who relied on cheap labor for weed control (Zhang et al., 2020) [46]. Herbicides became more accepted due to population growth, urbanization, and intensive agriculture. Today, herbicide use is essential for managing weeds, with over 60 herbicides and 700 formulations available, including combination products for broad-spectrum control (Brankov et al., 2021) [2].

Most common herbicides used for different food crops

Rice

Butachlor is a selective, pre-emergence herbicide primarily used to control annual grasses and some broadleaf weeds in rice fields. It belongs to the chloroacetanilide group of herbicides and works by inhibiting the synthesis of fatty acids in plants, preventing their growth. Butachlor is often applied to rice fields before or shortly after planting to prevent weed germination and control early weed growth (Ghrasiram et al., 2020) [9]. Butachlor inhibits the enzyme *acetyl-CoA carboxylase*, which is essential for fatty acid synthesis in plants. This disruption leads to stunted growth and eventual plant death. It is effective against a variety of grass weeds (e.g., *Echinochloacolona*, *Cynodondactylon*) and some broadleaf weeds. It is typically applied to flooded rice fields either before or shortly after sowing, and it needs to be incorporated into the soil for maximum efficacy (IIMR, 2021) [12]. Butachlor has moderate environmental persistence, with some concerns regarding soil and water contamination, especially in areas with heavy rainfall. It can have non-target effects on aquatic organisms if not properly managed. When used correctly, Butachlor is generally considered safe for rice crops, but overuse or improper application can lead to phytotoxicity and affect subsequent crops. It is important to follow recommended application rates and timings to avoid harm to the environment (Jat et al., 2020) [14].

Wheat

2,4-D Isoproturon is a combination herbicide that contains two active ingredients: 2,4-D and Isoproturon. It is used in agriculture to control a wide range of weeds in various crops, particularly in cereal crops such as wheat, rice, and maize. Each of the active ingredients in this formulation has a different mode of action, making it effective in controlling both broadleaf weeds and grasses (Kaur et al., 2022) [16]. 2,4-D: A systemic herbicide that primarily targets broadleaf weeds by mimicking the plant hormone auxin, leading to uncontrolled growth, which eventually kills the weed. It is a selective herbicide. A selective herbicide from the *urea* family that inhibits photosynthesis in weeds, primarily affecting grasses. It is often used in cereals to control grass weeds and some broadleaf weeds.2,4-D: Works by causing abnormal growth in weeds, leading to their death (Olesen and Bindi, 2022) [25]. It mimics auxin (a plant growth hormone), causing the plants to grow uncontrollably and eventually die. Isoproturon inhibits photosynthesis in weeds by blocking the photosystem II complex in chloroplasts, preventing energy production and causing plant death.2,4-D: Broadleaf weeds such as *Chenopodium album*, *Portulaca oleracea*, *Ambrosia artemisiifolia*, and others. Grasses and some broadleaf weeds in cereals, including *Echinochloa* species and *Avena* species (Rani et al., 2020) [28].

Characteristic, Mode and mechanism of new herbicides of an ideal herbicide

An ideal herbicide would possess several key characteristics that enhance its efficacy, safety, and environmental compatibility. Below, we outline the critical characteristics, modes, and mechanisms of action of new herbicides that can define them as ideal for modern agriculture (Singh et al., 2020) [34]. The herbicide should be effective at controlling a broad spectrum of weeds, including both grasses and broadleaf weeds, and should provide long-lasting control with a single application. It should selectively target weeds without harming the crop. The herbicide should ideally affect only the unwanted plants and not the crops or beneficial organisms in the environment. An ideal herbicide should have minimal impact on non-target organisms, such as beneficial insects, animals, soil microbes, and humans. It should be environmentally safe and not pose significant risks to biodiversity. The herbicide should work rapidly, showing visible effects on weeds within a short time (Su et al., 2020) [35]. Furthermore, it should degrade quickly in the environment to prevent accumulation in soil or water bodies, reducing environmental persistence. It should have a low residual effect in the soil, ensuring that it does not persist and affect subsequent crops or harm soil health. The herbicide should be affordable and economically feasible for farmers, both in terms of application costs and the value of the yield gains it provides. An ideal herbicide should be able to combat or delay the development of herbicide resistance in weed populations. This could be achieved through novel modes of action or a combination of modes that reduce the likelihood of resistance. It should be easy to apply using standard agricultural equipment and should have minimal special handling requirements (Abdullah et al., 2020) [1].The mode of action refers to the way in which the herbicide affects the plant. In the case of an ideal herbicide, it should: The herbicide should target critical metabolic processes that are essential for weed survival, such as photosynthesis, amino acid synthesis, fatty acid synthesis, or cell division. This ensures that the herbicide is highly effective in controlling a wide range of weeds (Zhao et al., 2023) [48].A modern, ideal herbicide should be able to target specific pathways or enzymes that are unique to plants or specific to weeds. This minimizes the risk of harming non-target organisms (e.g., crops, beneficial insects). Ideally, the herbicide should be systemic, meaning it is absorbed by the plant and translocated to different parts (roots, stems, and leaves), affecting the plant's overall growth and development. The herbicide should be effective both as a pre-emergence (before weeds sprout) and post-emergence (after weeds have sprouted) treatment, depending on the crop and the type of weeds it is targeting (CABI, 2022) [3].

Role of herbicide for the crop improvement

Weed Control Efficacy

Herbicides play a crucial role in enhancing the efficacy of weed control by providing a reliable and efficient means of managing unwanted vegetation in agricultural fields. By targeting specific biochemical processes in weeds, herbicides help to reduce competition for nutrients, water, and sunlight, which are essential for crop growth (Chen et al., 2021) [5]. Their use allows farmers to control a wide range of weed species, including both annual and perennial types, and prevent them from affecting crop yields. Herbicides can be applied selectively, ensuring minimal damage to the crops while effectively eliminating weeds (Zhao et al., 2022) [47]. With proper application, herbicides significantly improve crop productivity, reduce labor costs associated with manual weeding, and contribute to more sustainable farming practices by minimizing soil disturbance and promoting better crop health (Chen et al., 2024) [6].

Crop Performance

Herbicides play a vital role in improving crop performance by effectively managing weed competition, which can otherwise severely hinder crop growth and yield. Weeds compete with crops for essential resources such as water, nutrients, and sunlight, often leading to reduced crop vigor and productivity (Deng et al., 2021) [7]. By controlling weeds, herbicides help ensure that crops receive the maximum amount of these resources, leading to better growth and higher yields. Furthermore, herbicides reduce the need for manual labor, allowing farmers to focus on other critical aspects of crop management. Proper use of herbicides can also minimize soil disturbance and protect the crop from potential pest and disease outbreaks that weeds might harbor. Overall, herbicides contribute to healthier, more productive crops by maintaining an optimal growing environment (Hayyat et al., 2023) [10].

Environmental Impact

The environmental impact of herbicides is a significant concern in modern agriculture. While they are effective in controlling weeds and improving crop yields, herbicides can have adverse effects on ecosystems if not used carefully. One of the primary environmental risks is the contamination of soil and water resources (Heap, 2023) [11]. Herbicides can leach into the soil or be carried by runoff into nearby water bodies, potentially harming aquatic life and disrupting ecosystems. Additionally, non-target plants, including beneficial species such as pollinators, can be affected by herbicide drift, leading to a reduction in biodiversity (Ishfaq at al., 2020) [13]. Prolonged or excessive use of certain herbicides can also lead to the development of herbicide-resistant weed species, making future weed management more difficult. Furthermore, some herbicides may persist in the environment, affecting soil health and microbial communities that are essential for soil fertility. To mitigate these impacts, sustainable practices such as integrated weed management, careful application techniques, and the development of more environmentally friendly herbicides are being explored (Jiang et al., 2022) [15].

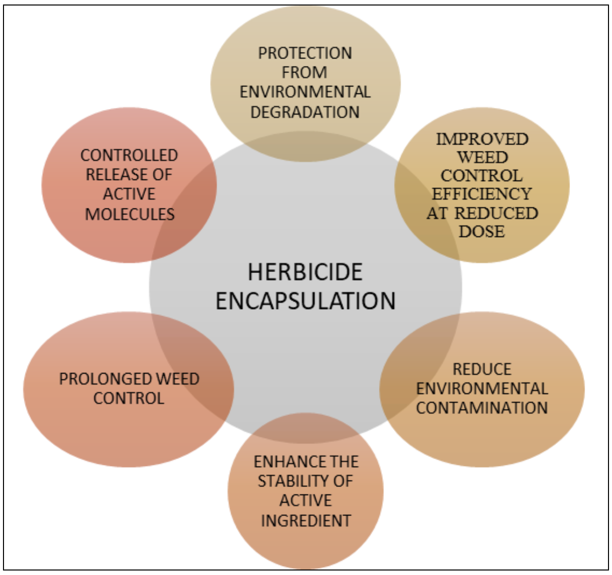

Fig 2: New systems for the delivery of herbicides to improve weed control efficiency

Cost-Effectiveness

The cost-effectiveness of herbicides is one of the key reasons they are widely used in modern agriculture. Herbicides provide a relatively low-cost solution for managing weeds compared to manual or mechanical weeding, which requires significant labor and time investment. By reducing the need for manual labor, herbicides help farmers save on wages, transportation, and equipment costs (Krishnaprabhu, 2020). Additionally, herbicides allow for faster and more efficient weed control, enabling crops to grow without competition for essential resources like water, nutrients, and sunlight, which ultimately leads to higher yields. When applied correctly, herbicides also reduce the risk of crop loss due to weed infestations, ensuring that farmers can maximize their productivity (Kurniadie et al., 2022) [19]. However, the cost-effectiveness of herbicides depends on factors like proper selection of the right herbicide for specific crops and weeds, application techniques, and avoiding overuse, which could lead to resistance and higher long-term costs. In the right circumstances, herbicides offer a valuable, cost-efficient tool for maintaining healthy crops and boosting agricultural productivity (Mendes at al., 2022) [22].

Herbicide molecules and their efficacy in rice: Case studies

Rice (Oryza sativa L.) is vital to India's economy, with increasing demand due to population growth. In Asia, uncontrolled weeds cause up to 50% yield loss in paddy fields, and weeds contribute to 12% of total crop yield loss. Effective weed management is crucial for rice production (Nath et al., 2022) [24]. Yield losses vary based on factors like rice system, variety, fertilizer, weed species, and climate. Weed competition is particularly intense in direct-seeded rice. Herbicide treatments affect weed dry weight and grain yield. Peng et al., (2020) [26] studied that Cyhalofop-butyl at 120 g/ha reduced weed dry weight to 42 g/m^2 and increased yield to 3.08 t/ha, while the weedy check had the highest weed dry weight (187 g/m^2) and the lowest yield (2.05 t/ha) (Table 1 Saini, 2003) [32]. According to Perotti et al., (2020) [27] Herbicide treatments like Bispyribac at 25 g/ha achieved 89% weed control efficiency (WCE) and a 2.5 t/ha yield, while pendimethalin at 1000 g/ha resulted in the lowest yield (1.03 t/ha). Statistically significant differences in grain yield were noted with a 0.39 t/ha threshold (Table 2 Malik *et al.*, 2009) [21]. Another study conducted by Saha et al., (2021) [30] (Table 3 Mishra *et al.*, 2007) [23] shows the effectiveness of herbicide treatments on *E. colonum* and *C. rotundus*. Penoxsulam24 SC at 25.5 g/ha (10 DAT) controlled 1 *E. colonum* and 3 *C. rotundus*, while the weedy check had the highest weed pressure (12 *E. colonum* and 21 *C. rotundus*). Similar resuls were found by Singh et al., (2001) [33] (Table 4 Reddy *et al.*, 2000) [29] who highlights that Fenoxyprop-p-ethyl + Ethoxysulfuron at 60+50 g/ha (15 DAT) resulted in 10.8 g/m^2 of weed dry matter and a yield of 5.89 t/ha, while the weedy check had 64.0 g/m^2 and a yield of 2.95 t/ha. Studies of Tan et al., (2022) [36] (Table 5 Saha, 2009) [31] shows that Bensulfuron-methyl + Pretilachlor at 50+50 g/ha (15 DAT) achieved 95% weed control efficiency (WCE) and the highest yield of 5.72 t/ha, while the weedy check had 0% WCE and a yield of 3.22 t/ha. Statistically significant differences were observed for WCE greater than 12.4% and yield differences exceeding 0.19 t/ha.

Herbicide molecules and their efficacy in wheat: Case studies

Wheat (*Triticum aestivum* L.) is a crucial global crop, grown on 219.04 million hectares. It faces diverse weed infestations influenced by agro-climatic conditions, cropping sequences, and tillage practices (Tan et al., 2021) [37]. Chemical weed control is commonly used due to high labor costs and challenges with manual weeding in broadcast sown fields. According to Tian et al., (2020) [38] who evaluated herbicide treatments over two years (2018-20) and found that Sulfosulfuron at 20 g/ha reduced weed dry weight to 61.4-67.8 g/m^2, with a weed control efficiency (WCE) of 28.9% and grain yield of 3737-3823 kg/ha. Chlorsulfuron at 30 g/ha resulted in the lowest weed dry weight (10.4 g/m^2) and highest WCE (88.1%), with a yield of 5491-5592 kg/ha. Another study conducted by Yi et al., (2020) [42] investigated that Metsulfuron at 4 g/ha reduced weed dry weight to 12.8-13.5 g/m^2, with a WCE of 85.6% and yield of 5484-5578 kg/ha. Triasulfuron at 60 g/ha reduced weed dry weight to 9.6-9.9 g/m^2, with a WCE of 89.3% and a yield of 5504-5618 kg/ha. Studies of Yuan et al., (2021) [43] revealed that Isoproturon at

1000 g/ha resulted in a weed dry weight of 54.0-62.0 g/m^2, with a WCE of 36.2% and a yield of 4019-4177 kg/ha. 2,4-D Na at 750 g/ha showed a weed dry weight of 17.2-19.4 g/m^2, with a WCE of 79.9% and a yield of 5076-5170 kg/ha (Table 6 Malik *et al.*, 2008) [20]. Similar results were found by Wang et al., (2022) [40] who studied the weed-free treatment, 100% WCE, and the highest yield (5682-5775 kg/ha), while the weedy check had the highest weed dry weight (84.7-97.2 g/m^2) and the lowest yield (3064-3456 kg/ha). According to the study conducted by Zahan et al., (2021) [44] Metsulfuron-methyl + surfactant (2.0 g/ha) reduced weed population to 75/m^2 with a yield of 5.71 t/ha, while Metsulfuron + 2,4-D (2+250 g/ha) reduced weeds to 23/m^2, yielding 5.69 t/ha. The weedy check had the highest weed population (361/m^2) and biomass (1063 kg/ha), with a yield of 4.65 t/ha (Table 7 Kurchania *et al.*, 2008) [18]. An investigation carried out by Xu et al., (2021) [41] revealed that Carfentrazone-ethyl (25 g/ha) reduced weed dry matter to 130 kg/ha, yielding 4.0 t/ha, while 2,4-D (500 g/ha) had a yield of 3.8 t/ha. The weedy check had the highest weed dry matter (1039 kg/ha) and the lowest yield (2.5 t/ha) (Table 8 Tripathi *et al.*, 2008) [39].

Table 1: Effect of Cyhalofop-butyl in Direct Seeded Rice (Saini, 2003) [32]

Treatment	Dose (g/ha)	Total weed dry weight(g/m^2)	Grain yield (t/ha)
Cyhalofop-butyldose (g/ha)	90	74	2.52
Cyhalofop-butyldose (g/ha)	120	42	3.08
Butachlor	1000	62	2.16
Weedy check		187	2.05
LSD(P=0.05)		11	0.41

Table 2: Effect of Bispyribac-sodium in Wet Direct Seeded Basmati Rice (Malik *et al.*, 2009) [21]

Treatment	Dose (g/ha)	Time (DAS)	Weed control efficiencyWCE (%)	Grain yield (t/ha)
Bispyribac	25	25	89	2.5
Pretilachlor+safener	500	5	54	1.7
Pendimethalin	1000	7	40	1.03
Weedy check	-	-	0	1.6
LSD (0.05)	-	-	-	0.39

Table 3: Influence of Penoxsulam on Weed Density (no/m^2) 40 DAT in Rice (Mishra *et al.*, 2007) [23]

Treatment	Dose (g a.i/ha)	Time of application (DAT)	*E. colonum*	*C. rotundus*
Penoxsulam24 SC	22.5	5	4	10
Penoxsulam24 SC	25.5	10	1	3
Butachlor 50 EC	1250	5	5	6
Weedy check			12	21
LSD(P=0.05)			0.9	1.5

Table 4: Effect of fenoxyprop-p-ethyl and ethoxysulfuron on weed control in rice (Reddy *et al.*, 2000) [29]

Treatment	Dose (g ha^{-1})	Time of Application (DAT)	Weed dry matter at 30 DAT	Grain yield (t ha^{-1})
Fenoxyprop-p-ethyl+ethoxysulfuron	60+50	15	10.8	5.89
Weed free			8.0	5.91
Weedy check			64.0	2.95
LSD(P=0.05)			12.4	0.49

Table 5: Effect of Bensulfuron-methyl on weed dry matter and grain yield of rice (Saha, 2009) [31]

Treatment	Dose (g ha^{-1})	Time of application (DAT)	WCE (%)	Grain yield(t/ha)
Pretilachlor	750	5	78	4.92
Bensulfuron -methyl	60	18	94	5.60
Bensulfuron-methyl +Pretilachlor	50+50	15	95	5.72
Weed free	0		100	5.86
Weedy check				3.22
LSD(P=0.05)			12.4	0.19

Table 6: Total dry weight of weeds and grain yield of wheat as influenced by different treatments (Malik *et al.*, 2008) [20]

Treatment	Dose (g ha^{-1})	Total weed dry weight (g m^{-2})		WCE (%)	Grain yield (kg ha^{-1})	
		2004-05	2005-06		2023-24	2024-25
Sulfosulfuron	20	61.4	67.8	28.9	3737	3823
Sulfosulfuron	25	53.6	59.3	37.9	3966	4134
Chlorsulfuron	10	32.9	36.6	61.8	4602	4800
Chlorsulfuron	20	19.5	20.8	77.9	5028	5201
Chlorsulfuron	30	10.4	11.2	88.1	5491	5592
Metsulfuron	3	21.6	24.4	74.7	4927	5144
Metsulfuron	4	12.8	13.5	85.6	5484	5578
Triasulfuron	20	27.0	30.6	68.3	4779	4937
Triasulfuron	40	13.3	13.4	85.4	5468	5545
Triasulfuron	60	9.6	9.9	89.3	5504	5618
Isoproturon	750	60.2	66.4	30.4	3782	3860
Isoproturon	1000	54.0	62.0	36.2	4019	4177
2,4-D Na	500	26.8	30.6	68.4	4707	4892
2,4-D Na	750	17.2	19.4	79.9	5076	5170
Weed free	-	0.0	0.0	100.0	5682	5775
Weedy	-	84.7	97.2	0.0	3064	3456
LSD (P=0.05)		3.5	3.8		221	233

Table 7: Effect of Metsulfuron-methyl on weed control and wheat grain yield (Kurchania *et al.*, 2008) [18]

Treatment	Dose (g/ha)	Weed population /m^2	Weed biomass (kg/ha)	Grain yield (t/ha)
1.Metsulfuron-methyl +surfactent (0.2%)	2.0	75	587	5.71
2.Metsulfuron +2,4-D	2+250	23	287	5.69
Weedy check		361	1063	4.65
LSD(P=0.05)			296	0.65

Table 8: Effect of different treatments on weed control and wheat yield (Tripathi *et al.*, 2008) [39]

Treatment	Dose (g/ha)	Dry matter of weed (kg/ha)	Effective tiller /m row	Grain yield (t /ha)
Carfentrazone-ethyl	25	130	61	4.0
2,4-D(sodium salt)	500	347	60	3.8
Weedy check		1039	41	2.5
LSD(0.05)		148	7.1	0.25

Conclusion

This review underscores the importance of evaluating new herbicide molecules for their efficacy in rice and wheat cultivation in India. As India continues to expand its agricultural production to meet growing food demands, the adoption of innovative herbicide solutions will play a crucial role in ensuring the sustainability of crop management practices. The previous works demonstrate that these newer herbicides offer significant advantages over conventional options in terms of weed control, crop yield, and environmental sustainability. New herbicide molecules show promise in enhancing weed control and crop productivity in rice and wheat farming in India. Fenoxyprop-p-ethyl + Ethoxysulfuron achieved the highest yield in rice, while Bensulfuron-methyl + Pretilachlor showed high weed control efficiency. In wheat, Chlorsulfuron delivered the best results, with the lowest weed dry weight, weed control efficiency, and better yields. Weed-free treatments always outperformed weedy checks. Novel herbicides with dual-action formulations provide effective weed control, reduced resistance, and lower environmental impact, supporting sustainable agriculture and soil health. Future studies should focus on long-term field trials and the integration of these herbicides into broader integrated pest management systems.

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