Review Article

Bio-efficacy of new molecules for weed management in grain legumes

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ABSTRACT

Grain legumes comprising pigeon pea, chickpea, peanut, soybean, lentil, cowpea, common bean, faba bean, pea, and horse gram are extensively cultivated globally. Higher protein content, coupled with symbiotic nitrogen-fixing bacteria in root nodules enabling nitrogen fixation, highlights their importance of minimizing fertilizer use in agricultural production systems. Legume cultivation is limited by prolonged weed interference which was managed either through mechanical/cultural or chemical or biological methods or combinations. Nevertheless, herbicides remain and will persist as a crucial and economical element in global crop cultivation. While first-generation herbicides benefit agriculture, their long-term persistence and off-target toxicity have significant negative consequences, causing harm to both the environment and humans. Moreover, weed resistance and similar chemistry enforce the demand for new modes of action. Therefore, continuous research into new herbicides is an important method for combating herbicide resistance and ensuring crop output. In recent years, a few herbicides with novel mechanisms of action have occurred. Plants treated with new-generation herbicides resulted in increased WCE (weed control efficiency), decreased weed dry matter, and seed yield. No phytotoxicity symptoms were observed on the existing and succeeding crops. Thus, this review deepens our understanding of human along with environmental health by emphasising the importance of ensuring that recently produced herbicides have high selectivity, low toxicity, target specificity, and minimal rates of application. Furthermore, it emphasises the significance of economic viability and environmental friendliness in these formulations.

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Keywords: *Modes of action, New-generation herbicides, Phytotoxicity, Selectivity, and Environmentally friendly*

1. INTRODUCTION

Generally, cultivating legumes provides resource and environmental benefits on a variety of dimensions, from small fields to the worldwide setting. Their impacts on pre-crop, supply of nitrogen, and the ability to promote nutrient as well as soil conservation contributes considerably to sustainable productivity of farm, resource conservation and emission reduction for a more ecologically friendly farming practice [1]. Their yield is limited by prolonged weed interference (Table 1.) which in turn elevates the production costs and diminishes the quality of produce [2]. These weeds were managed either through mechanical/cultural or chemical or biological methods or their combinations. However, herbicides will continue to serve as an effective and cost-efficient input in global crop production.

Table 1. Yield losses caused by weeds in various legumes

Legume	Yield loss [%]	References
Pigeonpea	31.0 to 52.8	[3]
Chickpea	77.8	[4]
Urdbean	43.3	[5]
Mungbean	38.6	[6]
Lentil	37.7	[7]
Field pea	50.0	[8]
Rajmash	49.5	[9]
Lathyrus	46.1	[10]
Mothbean	30-40	[11]

The evolving landscape and ongoing advancements in intensive agriculture are expected to continue relying on herbicides as a key tool for managing weeds. Generally, herbicide usage has proven effective in controlling weeds and significantly boosting crop yields. While first-generation herbicides had positive impacts on agriculture, they also introduced notable adverse impacts on the human health besides environment owing to their persistent nature and off-target toxicity. Recognizing these technical gaps in managing weeds presents comprehensive chances for innovative and creative solutions. The creation of new herbicide molecules emerges as one such solution. Growing awareness of human health and environmental underscores the importance of ensuring that recently developed novel herbicides exhibit high selectivity, low toxicity, target specificity, minimal rates of application, and remain both cost-effective and environmentally sustainable.

1.1 Trends in weed control systems through herbicides

The 2,4-D discovery in the 1940s marked the onset of a new era in weed management for modern agriculture. Subsequent decades saw a surge in chemical technologies for weed control, leading to the emergence of numerous herbicides targeting specific proteins. In the 50s and 60s, auxins, PS-I, and PS-II inhibitors were predominant, succeeded by cell division inhibitors as a main category in 60s and 70s. The 70s and 80s witnessed the introduction of various modes of action, such as EPSP inhibitors (glyphosate), carotenoid biosynthesis, PPOs, and fatty acid biosynthesis inhibitors. ALS inhibitors characterized the 80s and 90s, each mode enabling weed control in new crops. In the late 90s, advanced breeding skills facilitated the initiation of Herbicide Tolerance systems. Despite many outstanding herbicides now being off-patent, no novel mechanism of action has been identified in the past two decades. Trends in pesticide consumption and herbicide consumption pattern were presented in Table 2. Herbicides approved for use in different legumes are presented in Table 3. Further, herbicides banned, restricted in use and withdrawn in India and Kerala were presented in Table 4.

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Table 2. Trend in pesticide and herbicide consumption pattern in India (mt) [12]

S. No.		2016-17	2017-18	2018-19	2019-20	2020-21	2021-22	2022-23

	Pesticides							
1	India	58634	63406	59670	61702	62193	63284	52466
2	Kerala	895	1067	995	656	585	532	504
	Herbicides							
3	India	4075	2970	3998	4275	3297	2920	4155

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Table 3. Herbicides approved for use in different legumes [13]

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Crop	**Herbicides**
Chickpea/Lentil /Field peas	Fluchloralin 50% EC, Linuron 50% WP, Metribuzin 70% WP.
Pigeon pea	Alachlor 50% EC, Fluchloralin 50% EC, Pendimethalin 30% EC.
Black gram	Fenoxaprop-p-ethyl 9.3% w/w EC, Alachlor 50% EC, Imazethapyr 10% SL + Surfactant, Propaquizafop 10% EC, Quizalofop-ethyl 5% EC, Propaquizafop 2.5% + Imazethapyer 3.75% w/w ME, Fluchloralin 50% EC, Pendimethalin 30% EC.
Green gram	Alachlor 50% EC, Imazethapyr 10% SL + Surfactant, Pendimethalin 30% EC.
Groundnut	Fenoxaprop-p-ethyl 9.3% w/w EC, Quizalofop-ethyl 5% EC, Alachlor 50% EC, Alachlor 10% GR, Fluazifop-p-butyl 11.1% w/w + Fomesafen 11.1% w/w SL, Diclosulam 84% WDG, Imazethapyr 10% SL, Imazethapyr 10% SL + Surfactant, Pendimethalin 38.7% CS, Imazethapyr 35% + Imazamox 35% WG, Oxyflourfen 23.5% EC, Propaquizafop 2.5% + Imazethapyer 3.75% w/w ME.
Soybean	Alachlor 50% EC, Alachlor 10% GR, Bentazone 480 g/l SL, Chlorimuron Ethyl 25% WP + Surfactant, Clethodim 25% EC, Clomazone 50%EC, Diclosulam 84% WDG, Fenoxaprop-p-ethyl 9.3% w/w EC, Fluchloralin 45% EC, Fluazifop-p-butyl 13.4% EC, Pendimethalin 38.7% CS, Flumioxazin 50% SC, Propaquizafop 10% EC, Imazethapyr 10% SL, Haloxyfop R Methyl 10.5% w/w EC, Fluthiacet Methyl 10.3% EC, Imazethapyr 10% SL + Surfactant, Imazethapyr 70% WG + Surfactant, Metribuzin 70% WP, Pendimethalin 30% EC, Quizalofop-ethyl 5% EC, Pyroxasulfone 85% w/w WG, Quizalofop –p- tefuryl 4.41% EC, Sulfentrazone 39.6% w/w SC, Fomesafen 12 % + Quizalofop ethyl 3% w/w SC, Imazethapyr 35% + Imazamox 35% WG, Fluazifop-p-butyl 11.1% w/w +

	Fomesafen 11.1% w/w SL, Pendimethalin 30%+ Imazethapyr 2% EC, Propaquizafop 2.5% + Imazethapyer 3.75% w/w ME, Sulfentrazone 28% + Clomazone 30% WP, Sodium Aceflourofen 16.5% + Clodinafop Propargyl 8% EC.

Table 4. Herbicides banned, withdrawn, refused, and restricted for usage in India [14]

Banned	Nitrofen, Metoxuron, Paraquat dimethyl sulphate,
Withdrawn	Dalapon, Simazine
Refused registration	2,4,5-T, Calcium arsenate, TCA, Ammonium sulphamate
Restricted in use	2,4-D, Glyphosate (in some states), Dazomet (tea)

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2. Factors driving the need for novel modes of action

Following the initial detection of triazines resistance in weeds in the late 60s, Subsequent reports of categories resistant to almost all herbicides have been documented globally in over 154 distinct weed species [16]. The overutilization of a single mode of action all over crop rotation encourages weed shifts, leading to the herbicide resistance emergence.

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The need for innovative modes of action is driven by the prevalence of comparable chemistry, often distinguished by specific performance weaknesses. The identification of a promising herbicide often initiates the synthesis of analogs, sometimes resulting in a multitude of closely related products that target the same biochemical pathway. Within a mode of action group, certain compounds might exhibit comparable properties (Table 5).

Table 5. Characteristics of ALS-, ACCase- and PPO-inhibitors [17]

Characteristics	**ALS inhibitors**	**ACCase- inhibitors**	**PPO-inhibitors**
	Sulfonyl ureas	**FOPs**	**PPO**
Dose (g a.i./ha)	Very low (<100g)	Low (<500g)	Variable (50-2000)
Spectrum	Dicots+ monocots	Grasses only	Primarily dicots
Speed of action	Slow	Slow	Fast
Environmental risks	Carryover and soil mobility	Soil mobility	Phytotoxicity after drift

Elderly, high-dose formulations often lose registration because of elevated dosage requirements and persistent effects, primarily over concerns about groundwater contamination. Examples include urea herbicides (diuron) or triazines (atrazine or simazine). However, novel

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molecules may not always offer a comparable lasting impact or be cost-effective.

Herbicide resistance is a major concern in worldwide agricultural production. The demand for new herbicides develops as weeds gain resistance to existing formulations. Despite this demand, the development of herbicides with novel modes of action (MOAs) has been somewhat slow during the last two decades. As a result, the continual development of novel herbicides, including novel chemical classes or MOAs, remains an important strategy for combating herbicide resistance and ensuring sustainable agricultural production.

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3. New herbicide molecules

Farmers are progressively adopting a novel category of herbicides characterized by low application rates, which operate by inhibiting crucial plant enzymes. Referred to as Low Dosage High Efficiency (LDHE) compounds, these herbicides demonstrate exceptional effectiveness even at minimal doses. They offer several benefits compared to conventional herbicides (Table 6.).

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Table 6. Comparison of traditional and new generation herbicides

	Traditional herbicides	**New generation herbicides**
Dose	High	Low
Residual effects	More	Less
Effects on microbial populations	More	Less
Bio efficacy	Less	More
Mammalian toxicity	High	Low

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These innovative herbicide compounds allow for a significant reduction in chemical dosage, ranging from 100 to 1000 times less compared to conventional herbicides [18]. Despite such minimal application rates, these herbicides showcase exceptional herbicidal potency, contributing to their environmentally friendly profile.

3.1 Objectives for new herbicides

- Effective against both grass and dicotyledonous weeds
- Minimal application rates
- Versatility for application both before and after emergence
- Exceptional selectivity within specific crop production systems
- High safety standards
- Compatible with herbicide rotation regimes (e.g., resistance management)
- Favorable environmental performance

4. Recent progress in discovering herbicide new modes of action (MOAs)

The identification of herbicides through novel targets or MOA constitutes an ultimate approach to addressing weed resistance. However, only a limited number of herbicides with innovative MOAs have surfaced in recent decades (Table 7.).

Table 7. Novel mechanisms of actions [19]

New MOAs	Key enzymes	Herbicide
Fatty acid synthesis	Fatty acid thioesterases	Cinmethylin
Lipid biosynthesis	Very long chain fatty acid elongases (VLCFAE)	Chloroacetanilides (Eg: alachlor) Thiocarbamates (Eg: EPTC) Oxyacetamides (Eg: Flufenacet)
Plastoquinone biosynthesis	Solanyl disphosphate synthase (SPS)	Triketone herbicides Aclonifen
	Homogentisate solanesyl transferase (HST)	Cyclopyrimorate Haloxydine
Amino acid biosynthesis and protein regulation	Dihydroxy-Acid Dehydratase (DHAD)	Aspterric acid (*Aspergillusterrus*)
	3-Dehydroquinate Synthase	7-deoxy-sedoheptulose (7dSH)
	Serine/Threonine Protein Phosphatases (PPs)	Endothall Cantharidin
Acetyl CoA	Pyruvate Dehydrogenase Complex (PDHc)	Cyclic methylphosphonates
Histidine biosynthesis	Imidazole glycerol Phosphate Dehydratase (IGPD)	Tirazole phosphonates
De Novo pyrimidine nucleotide biosynthesis (Orotate pathway)	Dihydroorotate dehydrogenase (DHODH)	Tetflupyrolimet
Plastid synthesis	Peptide deformylase	Actinonin (Actinomycetes)

The levels of C_{14}:0 and C_{16}:0 saturated fatty acids in cinmethylin- treated plants are declined, signifying that both types of FAT proteins are inhibited by the herbicide. The direct relationship between cinmethylin (herbicide) and FAT proteins was recognized through co-crystallization within the FAT enzyme and fluorescence-based thermal shift experiments [20]. Herbicides that impede Very Long-

Chain Fatty Acid Elongases (VLFCAEs), such as oxyacetamides, thiocarbamates, and chloroacetanilides, are known to induce leaf twisting or curling [19].

Endothall and cantharidin exhibit a gradual and irreversible inhibition of Threonine/ Serine Protein Phosphatase activities [21]. Crystallographic studies have confirmed that aclonifen binds to SPS, leading to the decolorizing of treated plants by SPS blocking. Previous research established that haloxydine, serving as inhibitor of suicide that imitates the binding of homogentisate, may effectively block this enzyme. Furthermore, at a concentration of 25 uM, 7dSH significantly hampers plant development to a degree comparable to an equivalent dose of glyphosate, with 7dSH demonstrating activity in the low micromolar range [22]. Although lacking preemergence activity, 7dSH has proven valuable in post-emergence applications.

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Strong Isopropylmalate dehydrogenase (IGDP) inhibitors are triazole phosphonates [23]. Additionally, 1-alkylphosphonate derivatives that have significantly stronger herbicidal activity are substituted phenoxyacetoxy. particularly substituted phenoxyacetoxy compounds, exhibit markedly stronger herbicidal activity. Their efficiency in controlling broad-leaved weeds and sedges correlates with the inhibition of Pyruvate Dehydrogenase Complex (PDHc) [24].

5. Bio-efficacy of new herbicide molecules in different legumes

The cultivation of various legumes faces a significant challenge due to the pervasive issue of weed infestation, leading to a substantial reduction in yield. Major weed flora occurring in different legumes is present in Table 8.

Table 8. Major weed flora in different legumes

Crop	**Weed flora**
Chickpea	*Chenopodium album* L., *Sonchus arvensis* (L.), *Rumex dentatus* (L.), *Medicago denticulata (L.). Euphorbia geniculata* (L.)., *Physalis minima* (L.), *Cirsium arvense* (L.) *Scop and Vicia hirsuta* (L.) *Gray., Paspalidium flavidum* (L.)
Pigeon pea	*Echinochloa colona* (L.) *Link, Celosia argentea* (L.), *Commelina benghalensis, Cyperus rotundus* (L.), *Cynodon dactylon* (L.), *Cyperus iria* (L.), *Sorghum halepense* (L.), *Eleusine indica (L.),* and *Mollugo pentaphylla* (L.) *etc.*
Black gram	*Chloris barbata, Cyperus rotundus, Echinochola colonum, Digitaria longiflora, Commelina benghalensis, Trianthema portulacastrum*
Green gram	*Alternanthera sessilis, Amaranthus viridis, Commelina benghalensis, Cyperus rotundus, Cynodon dactylon, Corchorus acutangulus,*

	Panicum repens, Parthenium hysterophorous, Eleusine indica, Trianthema portulacastrum, Celosia argentea and *Digera arvensis*
Cowpea	*Acrachne racemosa, Eleusine africana/ indica, Setaria viridis, Brachiaria spp, Cynodon dactylon, Commelina benghalensis, Cyperus rotundus, Dactyloctenium aegyptium Echinocloa colona/ crusgalli, Rottboellia cochinchinensis (exaltata), Digitaria sanguinalis, Panicum spp, Phyllanthus niruri, Parthenium hysterophorus, Solanum nigrum, Trianthema portulacasttrum, Tribulus terrestris* and *Xanthium strumarium.*
Soybean	*Amaranthus viridis, Alternanthera philoxeroides, Cyperus rotandus, Cynodon dactylon, Celosia argentea, Dactyloctanium aegyptium, Euphorbia hirta, Euphorbia geniculata, Parthenium hysterophorus, Echinocloa colonum, Convolvulus arvensis, Alternanthera spp., Eleusine indica, Digitaria sanguinalis, Digera arvensis* and *Physalis minima, Phylanthus niruri,*
Groundnut	*Euphorbia geniculata, Alternanthera philoxeroides, Echinocloa colonum, Cynodon dactylon, Amaranthus viridis, Cyperus rotandus, Alternanthera spp., Eleusine indica, Euphorbia hirta, Dactyloctanium aegyptium, Phylanthus niruri, Parthenium hysterophorus, Convolvulus arvensis, Digera arvensis, Physalis minima, Celosia argentea, and Digitaria sanguinalis.*

To date, only few studies have been conducted on the application of novel herbicides to legumes. Nevertheless, the effectiveness of various novel herbicides has been evaluated through a comparative analysis involving parameters such as herbicide efficiency index (HEI), weed index (WI), weed counts, and weed control efficiency (WCE)

Fluchloralin, quizalofop ethyl, imazethapyr, and oxyfluorfen demonstrated safety in cultivation of chickpea. A notably reduced dry weight of weeds was detected under weed-free condition. Additionally, pre-emergence (PE) application of oxyfluorfen at 0.120 kg ha^{-1}, combined with hand weeding (HW) once and inter-cultivation (IC) once at 30-35 days after sowing (DAS), as well as fluchloralin at 0.675 kg ha^{-1} (PE) with imazethapyr at 0.050 kg ha^{-1} (PE), had comparable results in weed dry weight management. Significantly higher WCE (100%) was noted under weed-free conditions, followed closely by oxyfluorfen at 0.120 kg ha^{-1} (PE) with one HW and inter-cultivation once at 30-35 DAS (99.01%) and fluchloralin at 0.675 kg ha^{-1} (PE) with imazethapyr at 0.050 kg ha^{-1} (PE) (98.54%). The treatment with oxyfluorfen at 0.120 kg ha^{-1} (PE) combined with imazethapyr at 0.050 kg ha^{-1} (PE) resulted in significantly HEI and lower WI. However, the performance was comparable to the treatment involving fluchloralin at 0.675 kg ha^{-1} (PE) with imazethapyr at 0.050 kg ha^{-1} (PE) [25].

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The predominant control of narrow-leaved weeds was demonstrated by clodinafop-propargyl and quizalofop-ethyl, which presents a problem in the cultivation of chickpeas since broad-leaved weeds offer a serious hazard. Nonetheless, a wide range of weeds were successfully controlled by treatments using topramezone at 13.8 g per ha and clodinafop-propargyl in combination with Na-acifluorfen at 500 g per ha, which augmented seed yield, weed control index (WCI) and WCE [26]. The study also underlined the need for additional investigation to determine the best timing and dosage for various agro-ecological circumstances.

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An integrated approach involving imazethapyr at 75 g ha^{-1} (PE) at 10 days after sowing (DAS) along with post-emergence (PoE) application of quizalofop ethyl at 50 g ha^{-1} at 15 DAS, followed by one HW at 50 DAS, and a post-emergence tank mix application of 75 g of imazethapyr per ha along with 50 g of quizalofop ethyl per ha at 15 DAS, followed by HW once at 50 DAS, demonstrated effectiveness in diminishing weed density and their dry weight. This integrated approach resulted in higher WCE and lower WI, leading to a reduction in nutrient uptake by weeds when applied in pigeon pea [27].

According to [28], among various new herbicide molecules, the sodium acifluorfen 16.5% application combined with clodinafop propargyl 8% EC at 1250 ml ha^{-1} at 20 DAS exhibited superior performance, achieving WCI and WCE rates of 70.52% and 81.48%, respectively. The treatment having similar molecules applied at reduced rate of 1000 ml ha^{-1} also demonstrated significant effectiveness, with WCI and WCE rates of 63.91% and 79.42%, respectively. Overall, hand weeding two times at 20 DAS and 35 DAS showed notably better performance, followed by herbicide treatments.

The study in [29] reported that the highest WCE (95.20%) was achieved with PoE application of sodium acifluorfen 16.5% EC and clodinafop propargyl 8% EC at 250 g ha^{-1}. PE application of Diclosulam 84% WDG at 26 g a.i ha^{-1} showed a comparable WCE of 94.74% at 30 DAS. This trend persisted at 45 DAS (97.68% and 96.37%, respectively) and at harvest (92.15% and 90.59%, respectively). They were followed closely by tank mix application of imazethapyr 10% SL and quizalofop ethyl 5% EC at 125 g a.i ha^{-1} at 20 DAS (PoE) and tank mix application of pendimethalin 30% EC with imazethapyr 2% EC at 960 g a.i ha^{-1} (PE). The study concluded that diclosulam effectively controlled weeds until harvest because of its extended half-life, while imazethapyr and quizalofop ethyl decreased weed density through their dual mode of action. Imazethapyr targeted broad-leaved weeds by inhibiting ALS (acetolactate synthase) enzyme, and quizalofop ethyl aimed grass density by ACCase inhibition, causing weed death.

Weed management treatments resulted in higher dehydrogenase activity when compared to the weedy check at 30 DAS. The treatment involving stale seedbed and dry banana leaf mulching at 10 t ha^{-1} followed by quizalofop-p-ethyl at 50 g ha^{-1} (PoE) at 25 DAS exhibited the highest dehydrogenase activity, while the treatment with a normal seedbed + no weeding recorded the lowest dehydrogenase enzyme activity. This could be attributed to the reduced substrate obtainability caused by season-long weed invasion. Furthermore, diclosulam (PE) at 12.5 g ha^{-1} subsequently application of quizalofop-p-ethyl at 50 g ha^{-1} (PoE) at 25 DAS noted the highest urease enzyme activity, which was comparable to diclosulam (PE) at 12.5 g ha^{-1} followed by hand weeding once at 25 DAS and dry banana leaf mulching at 10 t ha^{-1}. They were followed by quizalofop-p-ethyl at 50 g ha^{-1} at 25 DAS. The observed differences in urease enzyme activity among treatments could be related to changes in the soil's pH and temperature [30].

The application of flumioxazin resulted in a 59% reduction in crop stands, while fomesafen + S-metolachlor led to an 11% decrease. Sulfentrazone-based programs exhibited variability, with pre-plant treatments typically showing fewer plants compared to pre-emergence treatments. Stunting was observed across various programs, with injury levels exceeding 20%. The flumioxazin programmes caused substantial crop damage, reaching 86% and 91%. Crop damage was exacerbated by excessive rains around planting time, which seeped the pesticide into the seed zone. However, the injury had largely reduced to less than 10 per cent by midseason. Injury from several sulfentrazone treatments *i.e.*, fomesafen + S-metolachlor, and both flumioxazin treatments persevered into midseason, surpassing 20%. Although higher damage in flumioxazin treatments raised concerns, the crop eventually recovered. The study also concluded that heavy rainfall had an adverse impact on the efficacy of residual herbicides [31].

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Combined chemical treatments, specifically UPH-203 at different rates (60.0, 80.0 and 100 g ha^{-1}) along with Na-Acifluorfen 10% SL at corresponding rates (123.7, 165, and 206.2 g ha^{-1}), demonstrated improved WCE compared to the application of individual chemical treatments. The reason for this improved performance is because weed species recovered more quickly after times when a single herbicide application was made. In terms of net production value (NPV), UPH-203 at 100 g ha^{-1} and Na-Acifluorfen 10% SL at 206.2 g ha^{-1} attained the maximum value at 1.15, followed by twice hand weeding (1.10). Remarkably, none of the treatments showed any signs of phytotoxicity, including stunted growth, hyponasty/epinasty, yellowing of the leaves, necrosis, wilting, *etc.* [32].

Among various herbicidal treatments, higher WCE of 72.71%, and a favorable B:C ratio of 1.75 were recorded with Imazethapyr + Propaquizafop at 75 + 62.5 g ha^{-1} applied at 20 DAS. This was followed by Imazethapyr at 100 g ha^{-1}, which resulted in a WCE of 70.76% and a B:C ratio of 1.57. Another effective treatment was Imazethapyr + Bentazone at 75 + 75 g ha^{-1}, which displayed a WCE of 68.38% and a B:C ratio of 1.60 at 45 days after application (DAA) [33].

In groundnut cultivation, diclosulam (PE) at 20 g ha^{-1} followed by HW once at 40 DAS resulted in a significantly decreased density and dry weight of total weeds, along with higher WCE. This was followed by another effective treatment, involving diclosulam (PE) at 20 g ha^{-1} followed by PoE application of cycloxydim at 100 g ha^{-1} at 20 DAS. This trend also interpreted a higher B:C ratio because of the reduced weeding costs and an increase in both pod and haulm yield [34].

Hand weeding produced higher weed-related measures in the study at 20 and 45 DAS. Compared to other herbicide treatments, acifluorfen 16.5% (PoE) + clodinafop-propargyl 8% EC (206.25 + 100 g ha^{-1}) had substantially better WCE, Weed Management Index (WMI), and HEI values of 90.22%, 1.37, and 10.64, respectively, and a lower WI of 4.07. Lower weed dry weight and increased pod yield from these treatments were linked to the higher HEI [35].

6. Phytotoxicity effect of new herbicide molecules in different legumes

[36] stated that In groundnut cultivation, treatments using twice the recommended doses of fenoxaprop-p-ethyl at 875 ml ha^{-1} and 1750 ml ha^{-1} did not show any phytotoxicity. A number of signs were included in the assessment, including leaf epinasty, chlorosis, vein clearing, resetting, tip burning, wilting, and necrosis.

According to [37], no phytotoxic effects were observed on blackgram at 3, 5, 7, and 15 DAA (days after application) of quizalofop-ethyl at 37.5 g ha^{-1} and fenoxaprop-p-ethyl at 100 g ha^{-1}. The study found that these herbicides were completely safe for the crop, as evidenced by the absence of phytotoxic symptoms such as epinasty, vein clearing, necrosis, hyponasty, and wilting. Additionally, there was no residual effect on the soil.

Assessing the phytotoxicity of herbicides using epinasty and chlorosis revealed that treatments with imazethapyr at 50 g ha^{-1}, imazethapyr + imazamox at 40 g ha^{-1}, and imazethapyr + imazamox at 60 g ha^{-1} exhibited phytotoxicity at 15 DAA [38]. These treatments resulted in bushy growth with narrow leaves, and due to the herbicides' greater toxic impact, chickpea plants did not recover well from the phytotoxic effects, which persisted until the blossoming stage. While the remaining treatments showed some degree of phytotoxicity, it was minimal, and the crop exhibited satisfactory recovery and growth.

In groundnut, diclosulam (PE) at 20 g ha^{-1} and subsequently application of cycloxydim at 100 g ha^{-1} at 20 DAS demonstrated superiority in suppressing growth of weeds during the early stages of fodder sorghum. This effectiveness was attributed to the extended herbicidal activity of diclosulam and a reduction in the weed seed bank. Crucially, no herbicide tested showed any negative effects on the dry fodder production, growth characteristics, or germination of the residual fodder sorghum crop [34].

7. Residual effect of new herbicide molecules in different legumes

Forage sorghum, mung beans, and cowpeas that were planted after the wheat crop showed no signs of fenoxaprop's 100 g ha^{-1} residual activity [38]. This indicates that the fenoxaprop application did not have a lingering impact that negatively affected the subsequent growth and development of these crops.

In white bean cultivation, crop injury tended to increase with the dose of imazethapyr. Specifically, when imazethapyr induced up to 62% observable injury when administered at a higher rate of 300 g ha^{-1}. This higher dose also led to a reduction in various growth parameters, including plant height, shoot and root dry weight and yield (32, 48, 20 and 77%, respectively), compared to the application of imazethapyr as pre-emergence at a lower rate of 50 g ha^{-1} [39].

The initial quizalofop-P-tefuryl residue concentrations in the plant and soil samples were 0.41 to 1.41 mg kg^{-1} and 0.95 to 2.3 mg kg^{-1}, respectively. The results indicated that the half-life values were 4.1 to 4.14 days for soil and 0.47 to 0.64 days for plants. The average recoveries were plant (85.33%), field soil (89%), and seed (86.33%), respectively. Importantly, residues were found to be less than the noticeable limit in all the harvested plant, seed, and soil samples regardless of treatments, suggesting that the use of quizalofop-P-tefuryl was considered completely safe for the blackgram crop in this study.

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The LOQ (limit of quantification) for quizalofop-p-ethyl, imazethapyr, and pendimethalin was 5.0 µg kg^{-1}, while for oxyfluorfen, it was 10.0 µg kg^{-1} [41]. Less than 11% separated the enlarged uncertainty for these herbicides' presence in peanuts. Importantly, the residues for these herbicides were less than the detection levels, indicating that they were not present or present at very low concentrations in the peanut samples.

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Imazethapyr residues were found in the soybean grain samples with amounts ranged from 0.006 to 0.018 g g^{-1} in all five different locations of a soybean field where the herbicide was sprayed (PoE) at a rate of 100 g ha^{-1} for weed control. However, residues were identified in the soil at one place having above 0.0015 µg g^{-1} and in other four locations it was below 0.0010 µg g^{-1}. Comparing the soil residues to the plant samples, they were generally lower. This research suggests that after applying imazethapyr to soybean crops, a pre-harvest period of 90-102 days is appropriate [42]. Additionally, the average imazethapyr recovery in grain, straw and soil of soybean was reported as 80%, 83% and 79%, respectively.

In a study using Ultrasonic Bath Assisted Extraction (USBE), the mean quizalofop ethyl recovery at different levels of fortification was determined to be 87.2% (soil), 83.4% (groundnut haulm), and 82.7% (kernel), respectively [43]. Based on the residues of quizalofop ethyl found in soil, groundnut haulm, and kernels at varying harvest times, the study also came to the conclusion that, in South India's tropical climate, the molecule can be used safely in groundnut to control grassy weeds at a dose of 50 g ha^{-1}, with a recommended pre-harvest interval of 110 days.

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Plots that received quizalofop ethyl at 100 g ha^{-1} had the highest concentration of its residue in the soil; these were followed by treatments that received 75 g and 50 g of ai ha^{-1}.

Across the various treatments, the mean concentration of residues ranged from 0.012 to 0.0384 µg g^{-1} in the soil. The decrease in the application dose resulted in a decrease in quizalofop ethyl residue concentration in the soil. Moreover, regardless the dosage of quizalofop applied, the concentration in groundnut haulm and kernel samples taken at harvest (110 DAA) was below the quantitative limit of 0.01 µg g^{-1}. Significantly, it was discovered that the residues were less than MRL (Maximum Residue Limit) *i.e.,* 0.05 µg g^{-1} set for crops including sugar beet and soybean. Additionally, even when the highest dose of quizalofop ethyl was administered *i.e.,*100 g ha^{-1}, the residues in groundnut kernels and haulm were substantially less than the MRL of 0.1 mg kg^{-1} [43].

8. Conclusion

Weed resistance to many of the herbicides now in use has grown widely, creating a need for novel herbicides with distinct Modes of Action (MOAs). Recent discoveries of promising herbicide targets and related herbicides offer potential solutions for managing resistant weeds. However, it is anticipated that weed evolution will lead to resistance against these new herbicides in the future. Therefore, the continuous development of herbicides with unique MOAs having high selectivity, slow resistance growth, and eco-friendliness is crucial for addressing both emerging and current herbicide resistance issues. Having a diverse set of "tools" in the form of herbicides is fundamental for effective weed management. This necessitates ongoing efforts in researching and developing new herbicide molecules. The application of these novel herbicides in legumes holds promise for sustainable cultivation through efficient weed management. However, extensive research is essential to optimize the dosage and timing of these new herbicide molecules under various agro-ecological conditions specific to legume crops to ensure the sustainable and effective use of these tools in weed control for legume cultivation.

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