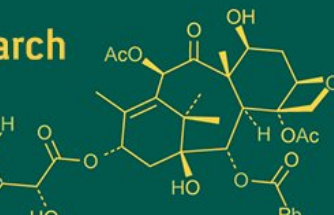
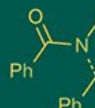


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Studies on the efficacy of different herbicides on Weed management in wheat (*Triticum aestivum* L.): A review

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Abstract

Wheat (*Triticum aestivum* L.) is one of the most important cereal crops of the world and occupies a strategic position in global as well as Indian food and nutritional security. The productivity of wheat is seriously constrained by intense crop-weed competition because weeds compete with the crop for light, nutrients, moisture and space during the early stages of establishment. Under changing labour availability, rising cost of manual weeding and increasing pressure on timeliness of field operations, herbicides have emerged as indispensable components of modern weed management in wheat. The present review synthesizes published information on weed flora associated with wheat, critical period of crop-weed competition, classification and comparative efficacy of pre-emergence and post-emergence herbicides, and their influence on weed control efficiency, crop growth, yield attributes and grain yield. The available body of literature indicates that herbicides such as pendimethalin, clodinafop-propargyl, sulfosulfuron, pinoxaden, metsulfuron-methyl, 2,4-D, carfentrazone-ethyl, pyroxsulam and ready-mix combinations including sulfosulfuron + metsulfuron and mesosulfuron + iodosulfuron effectively suppress grassy, broad-leaved and mixed weed flora when applied at appropriate dose and stage. Studies further revealed that efficient herbicidal weed management reduces weed density and dry matter accumulation, improves tillering, leaf area development and dry matter production, and ultimately enhances spike characters and grain yield over weedy check. However, repeated use of herbicides having similar mode of action has accelerated the evolution of herbicide resistance in problematic weeds, particularly *Phalaris minor*, and has raised concerns regarding residue persistence, shifts in weed flora, effects on soil biological health and environmental contamination. Therefore, sole dependence on chemical weed control cannot be considered sustainable in the long term. Integration of herbicides with competitive cultivars, stale seed bed, crop rotation, residue management, optimum sowing techniques and mechanical or manual interventions offers a more resilient approach. It may be concluded that herbicides remain highly effective tools for weed management in wheat, but their long-term usefulness depends upon judicious selection, rotation of modes of action and integration with ecologically sound weed management practices.

Keywords: Wheat, herbicides, weed management, integrated weed management, weed flora, grain yield

Introduction

Wheat (*Triticum aestivum* L.) is one of the most widely cultivated cereal crops and serves as a staple food for a large proportion of the world population. It contributes substantially to global food security by supplying calories, protein, minerals and several vitamins in human diets. Wheat grain is an important source of carbohydrates, moderate quality protein and dietary energy, and its wide adaptability has enabled cultivation under a broad range of agro-climatic conditions. In India, wheat constitutes the second most important food grain after rice and is central to the food economy of the Indo-Gangetic plains as well as many temperate and sub-tropical regions. Uttarakhand also maintains a significant area under wheat in plain and mid-hill agro-ecosystems where the crop supports household food needs as well as mixed farming systems. Despite major advances in varieties, fertilization and irrigation, wheat productivity is often limited by weed infestation, particularly during the early growth stages when crop growth is relatively slow and weeds establish rapidly^[12].

Weed infestation in wheat is a major agronomic problem because the crop is grown under irrigated as well as rainfed situations where a diverse complex of grassy and broad-leaved weeds emerges simultaneously with the crop. Problematic species such as *Phalaris minor*, *Avena ludoviciana*, *Chenopodium album*, *Melilotus indica*, *Anagallis arvensis*, *Rumex dentatus*, *Fumaria parviflora* and *Coronopus didymus* frequently reduce crop stand vigour, nutrient uptake and moisture availability. Researchers have reported substantial yield losses

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under unchecked weed growth, and the magnitude of reduction varies with weed flora, crop establishment method, fertility level and duration of competition. The critical period of crop-weed competition in wheat generally falls within the early growth phase, and failure to manage weeds during this interval causes irreversible yield reduction. Therefore, timely and effective weed control remains essential for realizing the yield potential of improved wheat cultivars^[3-6].

Manual weeding, though effective under limited situations, has become increasingly constrained by labour scarcity, high wages, adverse weather during peak season and the difficulty of selectively removing weeds in closely spaced wheat rows. Under such conditions, herbicides offer operational convenience, rapid weed suppression and greater field coverage within a short period. Over time, herbicidal weed management in wheat has evolved from single-spectrum products to selective and broad-spectrum molecules capable of managing grassy, broad-leaved and mixed weed populations. Nevertheless, intensive herbicide use has created new challenges in the form of herbicide resistance, weed shifts, residue carryover and ecological concerns. In this context, a comprehensive review of the efficacy of different herbicides in wheat is justified to synthesize current evidence on weed control, crop response, economics and sustainability and to identify future directions for integrated weed management^[7-10].

Materials and Methods

The present review was prepared through a critical appraisal of published literature on weed management in wheat with emphasis on herbicidal control. Relevant information was compiled from peer-reviewed research articles, review papers, technical bulletins, agronomy journals, weed science journals, institutional reports and related scholarly publications available through major academic databases and agricultural information portals. Literature dealing with weed flora in wheat, herbicide classification, timing and dose of application, weed control efficiency, crop growth response, yield attributes, grain yield, economics, herbicide resistance, residue behavior and environmental implications was screened and compared. Greater emphasis was given to recent studies while including selected earlier investigations that are foundational to herbicide recommendations in wheat. The extracted findings were synthesized comparatively to identify consistent trends, contrasting observations and practical implications for wheat-based production systems.

Weed Flora Associated with Wheat

The weed flora of wheat is highly variable and depends upon sowing time, irrigation regime, soil type, fertility status, tillage and climatic conditions. In north-western and north-central Indian wheat ecosystems, grassy weeds are often dominated by *Phalaris minor* and *Avena ludoviciana*, whereas broad-leaved weeds commonly include *Chenopodium album*, *Rumex dentatus*, *Anagallis arvensis*, *Melilotus indica*, *Lathyrus aphaca*, *Coronopus didymus* and *Fumaria parviflora*. The simultaneous occurrence of grassy and broad-leaved weeds complicates control strategies and often necessitates either broad-spectrum herbicides or combinations of herbicides. Studies revealed that unchecked mixed weed flora causes severe depletion of nutrients, soil moisture and solar radiation available to the crop, thereby restricting tiller formation and final yield^[11].

Critical Crop-Weed Competition Period in Wheat

The critical period of crop-weed competition in wheat has been widely recognized as the phase during which weeds must be controlled to prevent significant yield loss. Field experiments indicated that the early period extending roughly from 30 to 45 days after sowing is especially crucial under most wheat-growing situations, although the exact duration varies with cultivar, sowing method, weed density and environmental conditions. Researchers observed that weed competition during this period reduces plant height, effective tillers, dry matter accumulation and spike development. Consequently, herbicide application schedules in wheat are generally aligned with this biological window to secure early crop advantage and ensure efficient use of inputs^[5].

Classification of Herbicides Used in Wheat

Herbicides used in wheat can be classified according to time of application, target weed spectrum and mode of action. On the basis of time of application, they are broadly grouped into pre-emergence herbicides such as pendimethalin and post-emergence herbicides such as clodinafop-propargyl, sulfosulfuron, pinoxaden, pyroxsulam, metsulfuron-methyl, 2,4-D and carfentrazone-ethyl. On the basis of target spectrum, some herbicides are chiefly effective against grassy weeds, others against broad-leaved weeds, while several ready-mix formulations are designed for mixed weed flora. This classification has practical importance because herbicide choice in wheat must correspond with field weed composition, growth stage and risk of resistance development^[4].

Pre-emergence Herbicides in Wheat

Pre-emergence herbicides are used primarily to suppress the initial flush of weeds and reduce early crop competition. Pendimethalin has remained one of the most widely studied pre-emergence herbicides in wheat for control of several annual grasses and broad-leaved weeds when applied soon after sowing under adequate soil moisture. Researchers observed that pre-emergence application helps reduce early weed density and can be especially useful where post-emergence spraying is delayed. However, pre-emergence herbicides alone may not provide season-long control under heavy mixed infestations and therefore often require follow-up integration with post-emergence options^[7].

Post-emergence Herbicides in Wheat

Post-emergence herbicides form the backbone of weed management in wheat because they allow selection according to the weed flora actually present in the field. Clodinafop-propargyl, fenoxaprop-p-ethyl and pinoxaden are commonly used against grassy weeds, whereas 2,4-D, metsulfuron-methyl and carfentrazone-ethyl are widely adopted for broad-leaved weeds. Sulfosulfuron and pyroxsulam have shown wider utility against both certain grassy and broad-leaved weeds, while mesosulfuron + iodosulfuron and sulfosulfuron + metsulfuron are frequently reported as effective ready-mix options against mixed infestations. Field experiments indicated that timely post-emergence application at the recommended stage significantly lowers weed dry matter and enhances crop competitiveness^[17].

Broad Leaf Weed Management

Broad-leaved weeds in wheat can cause serious yield penalties when their density remains unchecked during the

vegetative phase. Herbicides such as 2,4-D, metsulfuron-methyl and carfentrazone-ethyl have been found effective against species like *Chenopodium album*, *Rumex dentatus*, *Melilotus indica* and *Anagallis arvensis*. Studies revealed that carfentrazone-ethyl is especially useful for hard-to-control broad-leaved weeds and that metsulfuron-methyl provides efficient control at comparatively low doses. Researchers also observed that herbicide performance improves when sprays are timed to coincide with the actively growing stage of the target weeds^[14, 24].

Grassy Weed Management

Grassy weeds, particularly *Phalaris minor* and *Avena ludoviciana*, are regarded as the most destructive weeds in irrigated wheat. Selective grass herbicides such as clodinafop-propargyl, pinoxaden and fenoxaprop-p-ethyl have repeatedly demonstrated satisfactory control of these weeds under many wheat production environments. Sulfosulfuron has also been effective against *Phalaris minor* in several studies, although its performance may vary depending on resistance status and soil conditions. Efficient grassy weed management is especially important because these weeds closely resemble wheat during early growth and therefore cannot be easily removed manually^[2].

Mixed Weed Management

Mixed weed flora in wheat necessitates herbicides or herbicide combinations capable of simultaneously controlling grassy and broad-leaved weeds. Researchers observed superior performance of sulfosulfuron + metsulfuron, mesosulfuron + iodosulfuron and pyroxulam under mixed infestations because these treatments reduced both weed density and weed dry matter more effectively than single-spectrum herbicides. Such broad-spectrum control is particularly advantageous in intensively cultivated areas where weed flora composition changes over time due to repeated herbicide use and altered crop management. The efficacy of mixed weed management strategies is reflected not only in weed suppression but also in improved yield attributes and grain yield^[27].

Herbicide Combinations and Tank Mixes

Herbicide combinations and tank mixtures have gained prominence in wheat because they widen the weed control spectrum and help delay resistance buildup. Studies revealed that combining herbicides with complementary modes of action often results in better suppression of complex weed populations than use of a single molecule. Sulfosulfuron + metsulfuron and clodinafop-propargyl followed by broad-leaved herbicides have frequently produced higher weed control efficiency and yield than individual treatments. However, compatibility, crop safety, spray timing and label recommendations must be carefully considered before adopting tank-mix strategies^[42].

Integrated Weed Management in Wheat

Integrated weed management in wheat combines herbicides with cultural, mechanical and preventive practices to improve sustainability and reduce overreliance on chemicals. Researchers observed that optimum seed rate, competitive cultivars, proper sowing time, stale seed bed, crop rotation, residue retention and hand roguing of surviving weeds strengthen the overall weed suppression programme. Herbicides remain important in this system, but

their role becomes more strategic and less repetitive. Such integration not only improves control of diverse weed flora but also minimizes selection pressure for resistant biotypes and helps maintain soil and environmental quality^[16].

Herbicide Resistance in Wheat Weeds

Herbicide resistance has emerged as one of the most serious threats to effective weed management in wheat, especially in regions where the same herbicide or mode of action has been used continuously for many years. The evolution of resistance in *Phalaris minor* has been extensively discussed in Indian wheat systems and has compelled shifts from one herbicide group to another. Researchers observed that resistance development is often accompanied by weed flora shifts and decline in field-level herbicide reliability. Therefore, resistance management through herbicide rotation, mixtures, dose optimization and integrated approaches is essential to preserve the efficacy of available herbicides^[10].

Environmental Impact of Herbicides

The environmental impact of herbicides in wheat depends on molecule, rate, persistence, soil properties, climatic conditions and method of application. When used judiciously, herbicides reduce repeated tillage and labour requirements, but indiscriminate use can contribute to off-target movement, contamination of water bodies and adverse effects on non-target organisms. Studies have highlighted that herbicide stewardship is necessary to minimize ecological risks while retaining agronomic benefits. Safe handling, adherence to recommended doses and avoidance of unnecessary repeat application are therefore central to environmentally responsible weed management^[21].

Herbicide Residue and Soil Health

Residue persistence and its influence on soil health have become increasingly important concerns in herbicide-based wheat production systems. Some herbicides may persist long enough to affect succeeding crops or interact with soil microbial activity under specific conditions of pH, temperature and moisture. Researchers observed that long-term sustainability requires attention not only to immediate weed control but also to residue carryover, microbial balance and soil biological functioning. Integration of herbicides with residue management, crop rotation and reduced chemical load can help mitigate these concerns^[31, 35].

Comparative Efficacy of Herbicides

Comparative evaluation across studies suggests that no single herbicide is universally superior under all situations, because field efficacy depends upon dominant weed flora, application timing, environmental conditions and resistance status. Nevertheless, a consistent pattern emerges wherein pinoxaden, clodinafop-propargyl and sulfosulfuron perform strongly against grassy weeds, metsulfuron-methyl and carfentrazone-ethyl are effective against broad-leaved weeds, and premix options such as sulfosulfuron + metsulfuron or mesosulfuron + iodosulfuron are often more effective under mixed infestations. Researchers observed that weed control efficiency under effective herbicidal treatments frequently exceeds 75 to 90 percent and is associated with marked grain yield improvement over

weedy check. Such comparative evidence demonstrates the importance of matching herbicide spectrum with actual weed composition rather than applying herbicides indiscriminately^[4].

Effect of Herbicides on Growth Parameters

Application of herbicides significantly influences wheat growth parameters mainly through reduction in weed competition. Field experiments indicated that successful weed control improves plant height, number of tillers per square metre, leaf area and crop dry matter accumulation by ensuring greater availability of nutrients, moisture and light to the crop. Researchers observed that effective post-emergence treatments generally produce better crop vigour than untreated control and are often comparable with weed-free situations under moderate infestations. The beneficial effect on growth parameters forms the physiological basis for subsequent improvement in yield attributes^[34].

Effect of Herbicides on Yield Attributes

Yield attributes such as ear-bearing tillers, spike length, grains per spike and test weight respond favourably when weeds are controlled during the critical competition period. Studies revealed that herbicidal weed management reduces sink limitation caused by crop stress and promotes better assimilate partitioning towards reproductive structures. As a result, treatments providing superior weed suppression also tend to record improved spike development and grain formation. This relationship is particularly evident where mixed weed flora is effectively managed through broad-spectrum herbicides or suitable combinations^[20].

Effect of Herbicides on Grain Yield

Grain yield response to herbicides in wheat is the cumulative outcome of weed suppression, improved crop

growth and better yield attributes. Researchers observed that herbicide-treated plots consistently out-yield weedy check and, in many cases, approach the yields obtained under weed-free conditions. The magnitude of yield gain depends on weed pressure and the suitability of the herbicide to the prevailing weed flora. Under severe infestations, timely and effective herbicide use can prevent major yield losses and substantially enhance production efficiency^[19].

Economics of Herbicide Application

Economic evaluation is critical in judging the practical utility of herbicide treatments in wheat. Studies revealed that although some ready-mix herbicides involve higher input cost, they often result in greater net returns and better benefit:cost ratio because of superior weed control and higher grain yield. Herbicide use is generally more economical than repeated manual weeding under conditions of labour scarcity and large field size. However, profitability depends on proper herbicide choice, dose, spray timing and avoidance of crop injury or unnecessary applications^[15].

Future Prospects of Weed Management in Wheat

The future of weed management in wheat lies in precision, diversity and sustainability. Researchers increasingly emphasize site-specific herbicide use, rotation of modes of action, decision support based on weed flora monitoring and integration of herbicides with conservation agriculture and other non-chemical measures.

Development of new herbicide mixtures, safer molecules, residue-aware recommendations and resistance surveillance will be essential. Greater attention is also needed to state-specific weed flora, including hill and tarai conditions of Uttarakhand, so that wheat weed management recommendations remain regionally relevant and ecologically sound^[26].

Table 1: Major weeds associated with wheat crop

Weed type	Scientific name	Common name	Nature of weed
Grassy	<i>Phalaris minor</i>	Little seed canary grass	Annual grassy weed
Grassy	<i>Avena ludoviciana</i>	Wild oat	Annual grassy weed
Broad-leaved	<i>Chenopodium album</i>	Bathua	Annual broad-leaved weed
Broad-leaved	<i>Rumex dentatus</i>	Jangli palak	Annual broad-leaved weed
Broad-leaved	<i>Anagallis arvensis</i>	Blue pimpernel	Annual broad-leaved weed
Broad-leaved	<i>Melilotus indica</i>	Senji	Annual broad-leaved weed
Broad-leaved	<i>Fumaria parviflora</i>	Gajri	Annual broad-leaved weed
Broad-leaved	<i>Coronopus didymus</i>	Swine cress	Annual broad-leaved weed

Table 2: Comparative efficacy of herbicides on weed control and yield

Herbicide treatment	Weed control efficiency (%)	Grain yield (q ha ⁻¹)	Yield increase over control (%)	Reference
Pendimethalin pre-emergence	65-78	38-46	18-30	7, 22
Clodinafop-propargyl post-emergence	75-88	40-50	22-38	2, 17
Sulfosulfuron post-emergence	72-89	41-52	24-42	2, 29
Pinoxaden post-emergence	80-92	42-54	26-45	4, 17
Metsulfuron-methyl post-emergence	70-86	39-48	20-34	14, 24
Carfentrazone-ethyl post-emergence	68-84	39-49	18-33	14, 24
Pyroxsulam post-emergence	82-93	44-56	28-48	12, 36
Sulfosulfuron + metsulfuron	85-95	45-58	30-52	6, 29
Mesosulfuron + iodosulfuron	84-94	44-57	29-50	27

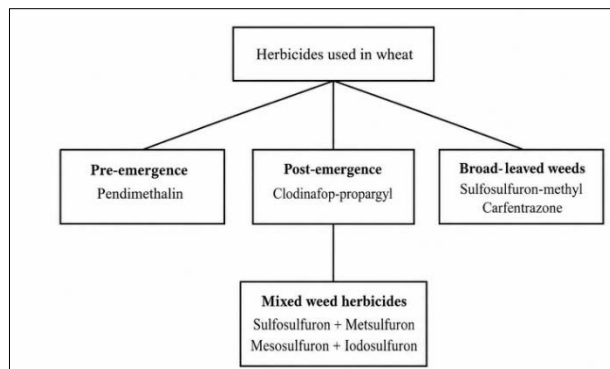


Fig 1: Classification of herbicides in wheat

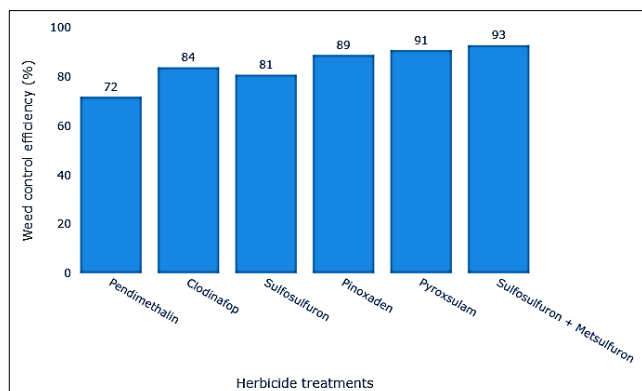


Fig 2: Comparative weed control efficiency of herbicides

Results and Discussion

The reviewed literature clearly shows that herbicides play a decisive role in suppressing weeds and safeguarding wheat productivity under diverse production conditions. Across studies, effective herbicidal treatments markedly reduced weed density, weed dry matter and nutrient depletion by weeds in comparison with untreated control. Post-emergence herbicides were especially effective because they allowed matching of treatment with the actual grassy, broad-leaved or mixed weed flora present in the field. Among individual herbicides, clodinafop-propargyl and pinoxaden were generally effective against grassy weeds, whereas metsulfuron-methyl and carfentrazone-ethyl provided reliable control of broad-leaved weeds. Under mixed weed situations, premix or broad-spectrum options such as sulfosulfuron + metsulfuron, mesosulfuron + iodosulfuron and pyroxulam frequently performed better than single-spectrum treatments.

A consistent finding across field experiments was that herbicide-induced weed suppression improved growth parameters of wheat, especially plant height, tiller density and dry matter accumulation. This improvement in vegetative growth translated into better yield attributes such as spike length, grains per spike and productive tillers, which ultimately resulted in higher grain yield over weedy check. Economic analysis in most studies also favoured herbicide use because increased grain yield and savings in labour cost improved net returns and benefit:cost ratio. However, the discussion emerging from recent literature also emphasizes that sole reliance on herbicides is neither ecologically desirable nor agronomically safe in the long term. Repeated use of the same active ingredient or herbicide group has led to resistance in troublesome weeds, particularly *Phalaris minor*, and has encouraged shifts in weed flora composition.

Another important outcome of the reviewed studies is that sustainability of herbicide-based weed management depends on informed and judicious use rather than indiscriminate application. Herbicide residues, possible effects on soil microorganisms, risk to non-target environments and carryover injury in succeeding crops require greater attention, especially under intensive wheat-based systems. Therefore, the most effective strategy emerging from this review is integrated weed management, wherein herbicides are used as one component of a larger programme involving crop rotation, stale seed bed, residue management, competitive cultivars and occasional manual or mechanical intervention. Such a strategy not only preserves the efficacy of herbicides but also improves resilience of wheat production systems against evolving weed problems.

Conclusion

Herbicidal weed management has substantially improved the efficiency of weed control in wheat and remains indispensable under present-day conditions of labour scarcity, large cultivated area and the need for timely field operations. The literature reviewed in this article indicates that selective and broad-spectrum herbicides, when applied at the proper stage and dose, effectively manage grassy, broad-leaved and mixed weed flora and significantly improve crop growth, yield attributes and grain yield. Among available options, post-emergence herbicides and suitable ready-mix combinations have shown particular promise under complex weed situations. However, continuous dependence on herbicides alone is associated with herbicide resistance, weed shifts, environmental concerns and residue-related issues. Therefore, the future of sustainable weed management in wheat lies in integrating herbicides with cultural, mechanical and preventive approaches, rotating modes of action and developing region-specific recommendations. In conclusion, herbicides are highly efficacious tools for weed management in wheat, but their long-term success depends upon scientifically guided, economically viable and ecologically balanced use.

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