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Weed management in cotton: Crop-weed competition, critical periods and integrated management approaches

G B Asiha[1], S Rathika[2*], T Ramesh[1], M Baskar[3] & K Sakthivel[4]

[1]Department of Agronomy, Anbil Dharmalingam Agricultural College and Research Institute (ADAC&RI), Tamil Nadu Agricultural University, Tiruchirappalli 620 027, Tamil Nadu, India

[2]Department of Agronomy, ICAR-Krishi Vigyan Kendra, Tamil Nadu Agricultural University, Sirugamani 639 115, Tiruchirappalli, Tamil Nadu, India

[3]Department of Soil Science and Agricultural Chemistry, Anbil Dharmalingam Agricultural College and Research Institute (ADAC&RI), Tamil Nadu Agricultural University, Tiruchirappalli 620 027, Tamil Nadu, India

[4]Department of Genetics and Plant Breeding, Anbil Dharmalingam Agricultural College and Research Institute (ADAC&RI), Tamil Nadu Agricultural University, Tiruchirappalli 620 027, Tamil Nadu, India

***Correspondence:** rathikas@tnau.ac.in

Abstract

Cotton (*Gossypium* spp.) is an economically significant fibre and cash crop, yet its productivity is considerably affected by weed infestation, especially during the initial phases of crop development. Because of its slow initial growth and broad plant type, cotton is very susceptible to competition from grasses, sedges and broad-leaved weeds; severe and prolonged weed interference can cause substantial yield losses, depending on weed pressure, duration of interference, cultivar and management intensity. This review synthesises the literature on weed flora composition, crop-weed competition, critical periods of weed interference and the effectiveness of weed management practices in cotton production, focusing on the competition for water, nutrients, light and growing space and their effects on crop growth and yield, nutrient uptake and economic returns. Evidence reviewed indicates that weed control is most critical during the early crop-growth period, commonly around 30–60 days after sowing (DAS), although the precise duration varies with production system and weed flora. Traditional hand weeding (HW) is effective but faces limitations due to labour availability and rising costs; selective pre-emergence (PE) and post-emergence (PoE) herbicides, including pendimethalin, metolachlor, pyrithiobac sodium and quizalofop-ethyl, control a wide range of weeds. Integrated weed management (IWM) can provide reliable and sustainable weed suppression by combining complementary practices; however, its benefits for crop yield and profitability are context-dependent and influenced by weed pressure, labour availability, production environment and management costs. The present synthesis is structured around the Indian production context, with a particular focus on Tamil Nadu, integrates evidence on weed suppression, crop performance, nutrient conservation and economics and considers herbicide resistance and herbicide-tolerant cotton technologies.

Keywords: cotton; crop-weed competition; integrated weed management; weed flora

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Introduction

Cotton (*Gossypium* spp.) is an important fibre and cash crop that supports textile industries, rural livelihoods and agricultural value chains in many cotton-growing regions (1). Worldwide, cotton is grown on 32.42 million ha and produces 1555 lakh bales with an average productivity of 756 kg ha^{-1}. India is the leading producer of cotton with 297.24 lakh bales (440 kg ha^{-1}) in an area of 11.48 million ha (2). Its productivity is strongly influenced by crop establishment, nutrient and water availability and timely management of biotic stresses. Among these constraints, weed interference is particularly important because cotton has relatively slow early growth and is commonly grown under wider row spacing, allowing weeds to establish rapidly and compete for water, nutrients, light and space (3). The magnitude of yield loss depends on weed species, density, time and duration of interference, crop growth stage, cultivar and environmental conditions. Therefore, the timing and type of weed-control treatment are important determinants of cotton productivity and economic returns. Traditionally, manual weeding or hoeing has been important, but now labour scarcity and high labour costs have led to reliance on herbicides and integrated approaches (4, 5). While there have been several reviews on weed flora, crop-weed competition and specific weed-control strategies in cotton, the literature is still scattered among critical-period studies, herbicide evaluations, integrated weed management (IWM) experiments, nutrient-removal studies and economic analyses. Unlike earlier reviews that have generally focused on individual

components of cotton weed management, such as weed flora, crop-weed competition or herbicide efficacy. This review integrates these components into a context-dependent framework for management decisions. The synthesis links the critical period of weed competition with weed spectrum, crop developmental stage, environmental conditions, labour availability, herbicide resistance risk and economic performance. Emphasis is given to Indian cotton production, with a specific focus on Tamil Nadu, while also considering cotton-based cropping systems and emerging management challenges. This framework is intended to distinguish situations in which manual, mechanical, chemical or integrated approaches are more appropriate rather than treating any single practice as universally superior.

Literature search and synthesis approach

The literature search was conducted in Google Scholar, Scopus, Web of Science (WoS) and ScienceDirect, supplemented by screening the reference lists of relevant cotton weed-management reviews. The search was conducted through August 2026. Search combinations included terms related to cotton, weed management, crop-weed competition, critical period, integrated weed management, pre-emergence (PE) herbicides, post-emergence (PoE) herbicides, weed-control efficiency, nutrient depletion, economics, herbicide resistance and herbicide-tolerant cotton. Publications from 1964–2026 were considered. Studies were included when they reported cotton-specific information on weed interference, critical periods, weed-control performance, crop growth or yield, nutrient removal, economic outcomes or sustainability-related effects. Studies were excluded when they were not directly related to cotton, did not provide relevant weed-management information, or lacked sufficient information for interpretation of the reported outcome. Duplicate records identified across databases were removed before screening. Titles and abstracts were screened for relevance, followed by assessment of the full text of potentially relevant studies. Since this was a narrative review, the literature was synthesised qualitatively and no formal meta-analysis or risk-of-bias scoring was performed.

Weed flora in cotton field

Environmental and edaphic conditions, including temperature, rainfall, soil moisture, soil texture, pH and management practices, regulate weed distribution, emergence and establishment, thereby largely influencing the weed spectrum in cotton fields (6). Weeds of cotton fields can be categorised into grasses, sedges and broad-leaved weeds based on their botanical nature. Several species in these groups have been reported to infest cotton. The major weed species reported in cotton fields (Table 1). Across the cited studies, grasses (notably *Cynodon dactylon* and *Echinochloa* spp.) and the sedge *Cyperus rotundus* L. are the most frequently reported and competitively important taxa across Tamil Nadu and other Indian cotton-growing tracts, while the broadleaf weed flora is more diverse and varies more strongly with locality (Tamil Nadu, Maharashtra, Gujarat, Karnataka); this pattern, rather than the species catalogue alone, should guide the choice of weed-control practice by agroecological zone and production system.

Crop-weed competition

The main weed species compete with cotton for the various resources (light, nutrients, water and space). Most weeds tend to outgrow cotton and therefore are a strong competitors for these resources, limiting growth and development of the crop. Crop-weed competition can be affected by the time of weed interference, weed density, species composition, growth stage of the crop and prevailing environmental conditions. Weeds are very competitive when they emerge with the crop or remain uncontrolled during the early growth period, interfering with crop growth and lint yields. Losses in cotton were high under extreme conditions of weed infestation and type (14). The intensity of crop-weed interactions is also influenced by environmental factors such as nutrient availability, water, light and temperature and can affect the success of weed control and management tactics (15). Thus, the availability of essential resources and the stage of crop growth are important determinants of the competitive relationship between cotton and weeds.

Demand for moisture

Weeds deplete soil water from crops, thereby depriving them of soil water for growth and development, which may result in a yield loss. Weeds were reported to extract 3–5 times more soil moisture than cotton. The weed competition was not as strong during the dry season as in the wet season (16). The concurrent growth of various weeds and crops leads to intense competition for soil moisture. *Echinochloa colona*, a C_4 plant known for its high-water use efficiency, can thrive under a range of soil moisture conditions, potentially leading to reduced crop yields (17). Thus, timely weed control helps conserve soil moisture and improve its availability for cotton growth and development.

Competition for space

Space is another important resource for which cotton and weeds compete and the intensity of competition is influenced by plant density and spatial arrangement. Cotton has relatively slow early growth and is often planted at wide row spacing that makes it easy for weeds to grow in the crop (18). Under these conditions, weeds can establish rapidly and occupy the available space before cotton develops an effective canopy. A well-developed crop canopy, achieved through optimal agronomic practices such as appropriate plant density, row spacing and timely planting, can inhibit weed emergence and growth (19). Appropriate spacing also maintains optimum plant population and promotes faster canopy development, thereby reducing opportunities for weed establishment and enhancing the competitive ability of cotton.

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Table 1. Predominant weed species reported in cotton fields

Weed category	Major weed species	Reference
Grasses	*Cynodon dactylon*, *Echinochloa crusgalli*	(7–9)
	Dactyloctenium aegyptium	(8–10)
	Echinochloa colonum, Chloris barbata	(11, 12)
	Eleusine indica, Digitaria sanguinalis	(13)
Sedges	*Cyperus rotundus*	(7, 11–13)
	Cyperus esculentus	(12)
Broadleaf weed species	*Trianthema monogyna*, *Convolvulus arvensis*, *Chenopodium album* and *Amaranthus spinosus*	(7)
	Commelina benghalensis, *Digera arvensis* and *Asphodelus tenuifolius*	(8)
	Parthenium hysterophorus	(8–10, 12)
	Cleome gynandra, Trianthema portulacastrum	(9)
	Acalypha indica, *Abutilon indicum*, *Euphorbia hirta*, *Croton sparsiflorus*, *Datura fastuosa*, *Boerhaavia diffusa*, *Indigofera ennaphylla, Corchorus trilocularis*, *Phyllanthus maderaspatensis*, *Amaranthus viridis*, *Amaranthus spinosus*, *Portulaca oleracea*, *Coccinia indica*, *Tridax procumbens*, *Leucas urticifolia*, *Priva leptostachya*, *Sonchus oleraceus*, *Oldenlandia umbellata*, *Vicoa indica* and *Malvastrum coromandelianum*	(10)
	Phyllanthus niruri, *Commelina benghalensis*, *Digera arvensis* and *Euphorbia hirta*	(11–13)
	Cleome viscosa, Tribulus terrestris and *Boerhavia erecta*	(12)

Demand for light

Cotton crops require 16 weeks to achieve 95 % canopy coverage, whereas weeds achieve the same coverage in just 8 weeks (16). This early growth allows weeds to intercept light available to cotton in the early stages of cotton growth. Shade (60 and 30 % of full sunlight coverage) in the form of *C. rotundus* and *C. esculentus* reduced production of crop dry matter, leaf area, rhizomes and tuber formation (15). Competition may start early in the season if weed populations are dense and smother crop seedlings (20). Improving light interception through appropriate plant density, row spacing and canopy development can increase cotton competitiveness against weeds by promoting earlier canopy closure and greater shading of weeds (21). Increased plant spacing and heavy fertiliser use during cotton hybrid production led to the proliferation of multiple weed species (8). Thus, optimising plant density and spatial arrangement is an important component of improving cotton competitiveness for light.

Demand for nutrients

Nutrient competition is a crucial factor in weed-crop interactions and contributes significantly to yield loss. The availability and application of nutrients can influence both cotton growth and the composition and competitiveness of the associated weed flora. High nitrogen (N) rates can significantly boost crop yield and reduce weed competition when weed densities are low (22). Grass weeds were stimulated by the high levels of N, phosphorus (P) and potassium (K) fertilisers, while the other broad-leaved weeds were not. However, pigweed populations remained generally unaffected by any treatment, except when P was added (23). These findings indicate that nutrient availability can influence weed species differently and may alter the competitive balance between cotton and weeds. The mineral nutrients are usually taken up by weeds at a greater rate and in relatively higher concentrations in their tissues than by some of the crop plants (20). Consequently, weeds can remove substantial quantities of nutrients from the soil and reduce their availability to cotton (24). Grassy weeds efficiently extract nutrients from the soil compared to cotton (25). Hence, successful weed control in time is crucial in reducing nutrient loss and retaining soil nutrients for cotton growth and productivity.

The competition for water, nutrients, light and space should not be considered as independent processes because limitation of one resource can modify the crop's ability to acquire and use other resources. During early crop establishment, dense weed populations can simultaneously reduce soil moisture and nutrient availability while intercepting light before cotton develops an effective canopy (22). The magnitude of these interactions is influenced by weed density, relative emergence time, species composition, crop developmental stage and environmental conditions. Under moisture-limited conditions, for example, competition for water may become more important, whereas under high fertility or favourable moisture conditions, rapid weed growth can intensify competition for light and nutrients (22). As the cotton canopy develops, its increasing interception of light can reduce the competitive effect of later-emerging weeds (20). Therefore, the competitive advantage of weeds changes dynamically with crop growth stage and environment, supporting the need for site-specific timing of weed management rather than reliance on a single resource-based intervention.

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Critical period of weed competition

The critical period varies with crop stage, weed density and species composition, so it is essential to identify this period and control weeds at the right time. The critical period of weed control (CPWC) comprises two related components: the critical period for weed removal (CPWR) and the critical weed-free period (CWFP) (26). The CPWR represents the latest point at which weeds can remain before their removal results in an unacceptable yield reduction, whereas the CWFP represents the minimum period during which the crop should remain weed-free to avoid unacceptable yield loss. Evidence from cotton production systems indicates substantial variation in these periods (Table 2), according to cultivar, weed species and density, emergence pattern, planting arrangement, soil moisture, temperature, rainfall or irrigation and management practices. In Tamil Nadu, available evidence indicates a critical period extending approximately from 15–60 days after sowing (DAS), whereas several studies from other production environments report important weed interference during approximately 30–60 DAS. These ranges should therefore be interpreted as evidence-based intervals rather than universal calendar recommendations. The appropriate weed-free and weed-removal periods should be determined according to local weed emergence and crop growth conditions. Fig. 1 illustrates the relationship among crop-weed competition, the CPWC and major weed-management approaches.

The substantial weed competition was frequently reported during the first 30–60 DAS; however, the magnitude and duration of interference varied with weed density, species composition, emergence timing, crop genotype and environment (27–31). Problems from weeds are especially severe if they appear at the same time as the crop or in large numbers, but later-emerging weeds tend to have a lesser impact on final crop yield as the canopy of cotton becomes competitive (4, 20). Estimates of yield loss vary among studies because they depend on the weed density, species, duration of interference, crop genotype and environment. The results therefore support a critical-period management strategy that is customised to local crop and weed conditions rather than based on a fixed calendar schedule.

Methods of weed control

Weed flora is complex and the critical period for weed competition is rather long, necessitating early and effective weed management. Weed infestation is controlled by a combination of weed-control methods including mechanical, biological, chemical and non-chemical (natural) (32). The efficiencies and drawbacks of each method of weed management are predictable and are dependent on the spectrum of weeds, stage of crop development, labour availability and production conditions. Most traditional and mechanical methods are laborious and expensive, particularly when there are insufficient labourers on the farm and prices are on the rise. Similarly, herbicides applied at sowing may not be effective for the entire season with the long-duration crop of cotton. Thus, the use of multiple weed-control techniques can give broad-spectrum and prolonged weed suppression and enhance cotton productivity (33). Long-term IWM has been shown to enhance cotton yield and profitability and the use of a combination of weed-control strategies is therefore recommended (34). Pre-emergence (PE) means herbicides applied before or soon after the crop is sown and PoE means herbicides applied after weeds have emerged. Weed-control efficiency (WCE) refers to the reduction in weed biomass that occurs when weed control is applied compared with the untreated situation; benefit-cost ratio (B : C ratio) is the economic return per unit of management cost; and ‘followed by’ (*fb*) indicates that weed control was applied sequentially.

Hand weeding

Hand weeding (HW) is a traditional and widely used method of weed control in cotton. The traditional and practical means of weed removal is manual, involving manual labour and simple hand tools (20). This approach is widely used and is generally safe for the crop and environment when properly implemented. Hand weeding has been reported to improve yield-related parameters and seed cotton yield compared with some chemical weed control treatments (35). Weeding three times (at 20, 40 and 60 DAS) proved to be the most effective treatment in cotton (36). The benefits of HW practice on seed cotton production were found to be 50.8 per cent higher than the weedy control, primarily due to the increase in bolls, boll weight and yield of seed cotton per plant (37). Similarly, two HWs resulted in higher dry matter production, N uptake, seed cotton yield, lint yield and N use efficiency (38).

The effectiveness of HW has also been demonstrated with respect to timing and frequency of operation. Two HW operations at 30 and 60 DAS gave the greatest WCE (25) and the maximum yield of 1148 kg ha^{-1} of seed cotton (39). In cotton, HW twice decreased the density of weeds and resulted in an increased height of the plant, number of sympodial branches per plant, bolls per plant and seed yield (40).

The highest percentage of WCE was recorded when the weeding was done twice, followed by earthing up (41). Reported optimum timings vary somewhat across studies (25 and 45 DAS; 20 and 40 DAS; a single weeding at 45 DAS), a pattern that reflects differences in weed-emergence timing, irrigation regime and cultivar between trials rather than conflicting recommendations. Weeding at 25 and 45 DAS had a significant impact on reducing total weed density and total weed dry weight in cotton (9). In the same way, HW at 20 and 40 DAS resulted in better plant height, leaf area index (LAI) and dry matter production at various growth stages of the crop (42). Lower weed dry weight and increased nutrient uptake were observed with HW at 45 DAS (43). Despite its effectiveness, the high labour requirement, time consumption and increasing cost of manual labour limit the wider adoption of HW in cotton.

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Table 2. Reported critical period of crop-weed competition in cotton, by region and production system

Region/production system	Critical period (DAS)	Basis/cultivar	Reference
Zambia, tropical black clay soils	~50 (first 50 days)	General field observation	(27)
India, general	40–60 (no gain from weed–free beyond this)	Weed removal timing trial	(28)
India, general	35–50	Interference-period study	(29)
Tamil Nadu, India (zero-till cotton)	15–60 (wider period)	Zero-till system	(30)
Narrow row-spacing systems	30–60 (~50 % of crop life)	Row-spacing × duration study	(31)
Composite estimate	30–60	Central tendency across the above	(20, 27–31)

DAS: days after sowing.

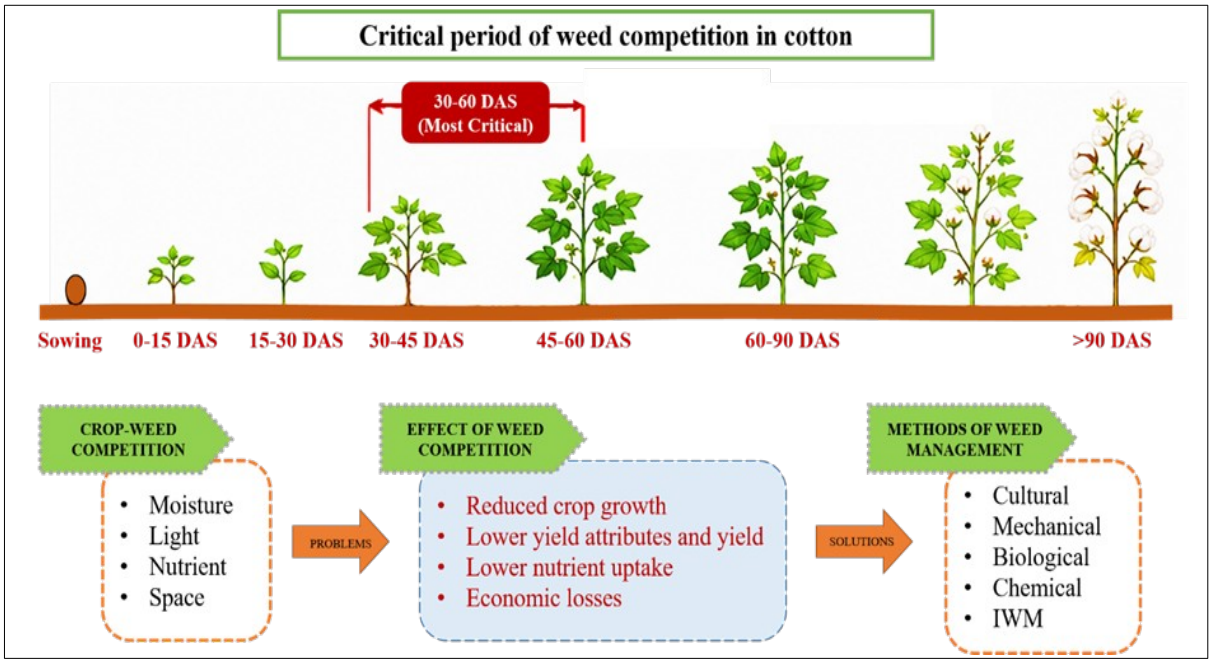


Fig. 1. Conceptual framework of crop-weed competition, critical period and weed management in cotton.

These limitations have increased the importance of chemical and IWM approaches, discussed in the following sections.

Chemical method of weed management

Although HW provides effective weed control, its high labour requirement and cost render herbicides an important alternative, particularly during periods of peak weed infestation and labour scarcity (44). Selective PE and PoE herbicides can control different categories of weeds and provide complementary control, although repeated use of the same herbicide increases selection pressure for resistance; herbicides are therefore best used as part of diversified IWM programmes rather than as a stand-alone, one-off solution. Herbicide choice and availability in India are further constrained by pesticide-registration status and periodic restriction notifications issued by the regulatory authorities and practical recommendations should take this regulatory context into account.

In labour-deficient regions, herbicides can be particularly appealing to farmers and may be more cost-effective than mechanical and manual work in regions of high labour costs. They can be used in place of mechanical weed control in many cases and, as a result, can minimise mechanical damage (stalk breakage, lodging, uprooting and root damage) to crops. As a result, the demand for selective PE and PoE herbicides for effective weed control during the entire growing season exists (45). However, there are significant trade-offs with repeated and intensive use of herbicides, such as development of resistance to herbicides among weed populations, reliance on a limited number of effective modes of action and carry-over effects on subsequent crops (46). Herbicides should be combined with cultural and mechanical and other complementary practices and used in rotation with other herbicides (where possible) rather than as the only method for controlling weeds.

Pre-emergence

Pre-emergence herbicides are applied before weed emergence, generally before or shortly after crop sowing, depending on the product and label recommendation (47). Usually, these herbicides are applied on the soil surface and should be capable of penetrating to 3.5–4 cm below the soil surface when irrigation water is applied to eliminate germinating weeds (48). Among the PE herbicides used in cotton,

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pendimethalin and metolachlor have been widely evaluated for early-season weed management; non-chemical cultural and mechanical alternatives (below) remain the mainstay of weed control in organic cotton production, where herbicide use is precluded.

Pendimethalin

Pendimethalin is a herbicide applied to control grasses and broad-leaved weeds in field crops, such as cotton. It is a selective herbicide belonging to the dinitroaniline group. It is absorbed primarily via the roots and shoots of germinating weeds and inhibits cell division and elongation, leading to the death of susceptible seedlings shortly after germination (49). Pendimethalin is an effective herbicide that has been used for many years in cereals, oilseeds, vegetables and other crops (50). Pendimethalin is a PE herbicide, typically for cotton, applied with one or more intercultural operations to help control weeds for a longer period (6).

Several studies have demonstrated the effectiveness of pendimethalin when used alone or in combination with manual weeding. The use of pendimethalin alone at 0.67 kg ha^{-1} reduced the weed counts and increased the yield (51). Lower rates of pendimethalin and a single HW also yielded significantly higher seed cotton production than did higher rates of pendimethalin alone (52). Pendimethalin applied at 1.0 kg ha^{-1} in a dry bed furrow before the first irrigation provided 82.5 % control of the broadleaf weeds and 84.1 % control of the narrow-leaf weeds (53). In the same way, pendimethalin at 1.0 kg ha^{-1} followed by HW at 30 and 60 DAS reduced weed density and dry matter of the weeds, gave the highest efficiency of weed control and gave the highest seed cotton production (54).

The efficacy of pendimethalin has also been demonstrated under different application rates and management conditions. The research results indicated that the PE application of pendimethalin (38.7 % EC) at 2.0 kg ha^{-1} followed by HW and earthing up at 45 DAS was effective for the control of grass, broad-leaved weeds and some sedges because pendimethalin is a broad-spectrum herbicide (55). This also led to lower weed dry weight and higher cotton yield and net returns for irrigated production (8). Grasses take up herbicide through the coleoptile and the developing shoots below the soil, inhibiting susceptible seedlings.

Also, in each case, applying pendimethalin at 1 kg ha^{-1} at 3 DAS and HW at 30 DAS or 40 DAS resulted in higher seed cotton production and lower weed dry weight (12, 45). Overall, these studies indicate that pendimethalin is particularly effective for early-season weed suppression, while its integration with subsequent HW can extend weed control and improve cotton productivity.

Metolachlor

Metolachlor is a PE herbicide particularly effective against annual grassy weeds and selected broad-leaved weeds. It acts as a growth inhibitor once absorbed through the roots and shoots of target weeds by disrupting the production of chlorophyll, proteins, fatty acids, lipids, isoprenoids (gibberellins) and flavonoids (anthocyanins) (56). It is used to manage certain broadleaf weeds and annual grassy weeds, such as *Cyperus esculentus*, *Panicum dichotomiflorum*, *Digitaria* spp., *Echinochloa crusgalli* and *Setaria* sp. In cotton fields, pendimethalin application (1 kg active ingredient ha^{-1}) and metolachlor (2 kg active ingredient ha^{-1}) (57) should be effective against *Cyperus rotundus* and *Trianthema portulacastrum*. Pre-emergent application of metolachlor at 1.9 kg active ingredient ha^{-1} resulted in a 93 % reduction in weed density when compared with untreated checks and a 40 % increase in lint yield (50). Moreover, PE application of metolachlor did not adversely affect the distribution of fruit across horizontal or vertical fruiting positions in cotton (58).

Metolachlor and fluometuron in combination (1.0 kg active ingredient ha^{-1}) was most effective in reducing dry weight of weed (59). The biomass of *C. rotundus* remained significantly reduced by 86 % with application of metolachlor at 2.15 kg active ingredient ha^{-1} (60). Combining glyphosate with either pendimethalin or metolachlor achieved substantial weed control, reaching 90–95 %, compared to manual weeding, which achieved 88 % control. In contrast, metolachlor alone provided 57 % WCE (32). On the other hand, when sorghum and sunflower water extract (1.5 L ha^{-1}) were combined with metolachlor (0.72 kg active ingredient ha^{-1}), these treatments also resulted in efficient weed control and yield of seed cotton (61).

Post-emergence herbicides

Post-emergence herbicides complement PE treatments by controlling weeds that emerge later in the crop season. These herbicides target actively growing weeds and are crucial for effective weed management in cotton fields ensuring that cotton plants receive adequate nutrients, water and sunlight (62). The effectiveness of sequential herbicide applications highlights the importance of combining different weed-control timings.

Post-emergent treatments with pyrithiobac sodium and quizalofop-ethyl demonstrate the benefit of using complementary weed spectra. Pyrithiobac sodium works best on broad-leaved weeds while quizalofop-ethyl works best on grassy weeds (63, 64). The combination of pyrithiobac sodium 0.032 kg ha^{-1} followed by quizalofop-ethyl 0.025 kg ha^{-1} gave the least weed dry weight and the average yield of 2270 kg ha^{-1} of seed cotton (65). One hoeing at 45 DAS with Pyrithiobac sodium at 0.062 kg ha^{-1} plus quizalofop-ethyl at 0.050 kg ha^{-1} also reduced grass and broad-leaved weed density (66) and dry weight (67).

A sequential programme of pendimethalin at 0.75 kg active ingredient ha^{-1} (38.7 EC) at the 2–4 leaf stage of weeds followed by pyrithiobac sodium at 0.062 kg active ingredient ha^{-1} (10 SC) plus fenoxaprop-p-ethyl produced 2201 kg ha^{-1} seed cotton, 86.37 % WCE and a B : C ratio of 2.58 (68). Pyrithiobac sodium at 0.060 kg ha^{-1} plus quizalofop-ethyl at 0.050 kg ha^{-1} produced WCE values of 71.54, 63.18, 60.35 and 58.01 % at 60, 90, 120 DAS and harvest, respectively (62). These findings indicate that sequential programmes can

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maintain weed control outside the herbicide period, but they are reliant on rainfall, soil type, temperature, weed-emergence pattern and crop growth stage.

Sequential and tank-mix programmes have also been effective in controlling weeds in Bt cotton (69, 70). Inter-cultivation plus HW at 20, 40 and 60 DAS was reported as effective alternatives, together with a programme of pendimethalin 38.7 % CS at 0.50 kg ha^{-1} followed by oxyfluorfen at 0.05 kg ha^{-1} as PE with pyrithiobac sodium at 0.062 kg ha^{-1} plus quizalofop-ethyl at 0.05 kg ha^{-1} as PoE (71). The findings lead to a larger synthesis: herbicide sequences can increase the control period and the weed control spectrum and mechanical or manual control can offer additional weed control in the late season and diversify weed management.

Post-emergence management with glyphosate is an example of the need to match the production system and cultivar to the herbicide strategy. Weed dry weight was decreased by glyphosate at 5.4, 3.6 and 2.7 kg active ingredient ha^{-1} around the critical weed competition period in glyphosate-tolerant cotton (9). In conventional rainfed cotton, PE pendimethalin followed by PoE glyphosate, combined with HW and hoeing, was reported to give season-long management but with reported WCE of only 27 % (25). These findings indicate that glyphosate efficacy should be interpreted in relation to crop technology, weed spectrum, application timing and resistance risk. The evidence indicates that herbicide selection should be based on crop technology, weed spectrum and local herbicide resistance risk and non-chemical management strategies should be used alongside chemical management to enhance the reliability and sustainability of weed management.

Integrated weed management (IWM)

Integrated weed management is an approach that is based on comprehensive land use planning to avoid the aggressive invasion of weeds and to increase the competitive advantage of crop plants (20). It is the careful combination of chemical, cultural, mechanical, biological and other appropriate weed control methods to achieve efficient, long-lasting weed control. Conservation agriculture and weed management can be integrated to enhance weed suppression and yield and soil biological status of cotton-based cropping systems (72). Mechanical and conservation-agriculture-based weed management also has implications for soil biological health and structure, since reduced tillage and residue retention influence soil microbial activity and long-term fertility alongside their effect on weed suppression (19, 72–75). Weed spectrum and the optimal IWM strategy further differ under cotton-based cropping systems such as cotton-wheat and cotton-babycorn-sunnhemp rotations, where residual weed pressure and species composition carried over from the preceding crop must also be considered (5, 72).

The data from multiple studies show that IWM is most effective when other tactics are intentionally integrated to provide cotton protection during the critical period and into the period where a tactic is inactive (73). The weed densities of 23.8 and 21.8 plants m^{-2} were obtained at 30 and 60 DAS, respectively, when pendimethalin was applied at 1.0 kg ha^{-1} and hand weed at 30 and 60 DAS, respectively, with a 68.20 % WCE (54). The benefit of IWM, however, is not necessarily that all individual components are better than herbicides, but that there are fewer control gaps and less reliance on a single weed-control approach.

When weed emergence is prolonged, sequential PE and PoE herbicide programs are very helpful. A PE pendimethalin programme followed by PoE pyrithiobac sodium and inter-cultivation yielded low weed biomass, 7.19 % weed index and minimal weed P removal of 2.93 kg ha^{-1} (76, 77). By the same method, pendimethalin (0.75 kg active ingredient ha^{-1}) PE and pyrithiobac sodium plus quizalofop ethyl (25 DAS) and inter-cultivation (55–60 DAS) reduced the weed density and increased the WCE to 82.39 % (78–80). Combined, these results suggest that the successful IWM programmes most often include a combination of early-season residual control and a later, targeted intervention and, if possible, a mechanical operation.

The effectiveness of IWM also relies on the interplay of the four factors: timing of treatment, weed spectrum, crop production system and environmental conditions. Chemical combinations are effective at providing broad-spectrum suppression and mechanical or manual methods can be used to control weeds that have survived or emerged late. The emergence and community structure of weeds is also influenced by conservation-agriculture practices (74, 75). Integrated weed management tends to outperform single-tactic control where weed emergence is prolonged, weed pressure is high, or labour is scarce, whereas a single well-timed tactic can be equally effective and more economical where weed pressure and the critical period are both short (5, 25, 69). Therefore, IWM should not be considered as a fixed set of practices, but as a flexible, site-specific approach. The major benefit is the ability to provide effective weed control without relying on any one control technology and enhance the resilience and sustainability of cotton production.

Effect of integrated weed management on growth attributes

Effective weed suppression reduces resource competition and consequently improves cotton growth. Integrated weed management also increases the ability of cotton plants to develop canopy and biomass by reducing competition for water, nutrients, light and space during critical times. Maximum LAI was observed with pendimethalin at 1.5 L ha^{-1} followed by HW at 40 DAS (81). Pre-emergence pendimethalin at 1 kg ha^{-1} followed by PoE quizalofop-ethyl at 0.05 kg ha^{-1} applied at 30 DAS resulted in increased plant height along with weed management (82, 83). The plant height was higher in Pendimethalin at 2.0 kg ha^{-1} + HW (55). With PE pendimethalin at 0.75 kg ha^{-1} and PoE pyrithiobac-sodium at 0.062 kg ha^{-1} (84), taller plants were observed. The plant height and number of monopodial branches per plant in cotton (85) were maximum in the case of PE treatment with pendimethalin and PoE

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application of pyrithiobac sodium. Hand hoeing applied twice in combination with metolachlor and then cotton plants attained a height of 96.60 cm (86). The PoE application of pyrithiobac sodium (0.062 kg ha^{-1}) at 30 DAS plus HW at 60 DAS recorded a height of 42.4 cm at harvest stage. Additionally, the leaf area per plant measured 10.9 dm^2 and the plant dry weight was 18.5 g $plant^{-1}$ at the harvest stage during the 2019–20 growing season (87). Thus, effective IWM promotes better crop growth.

Effect of integrated weed management on yield, nutrient conservation and economics

The benefits of effective weed control in terms of increased crop growth are evident in the increase in yield attributes and seed cotton yield (Table 3). Weed control in the critical period eliminates a competitor for the essential resources and helps to increase numbers of bolls, boll weight and cotton production.

Economic performance is a key metric to determine whether enhanced weed control justifies the additional expense. Sequential and integrated programmes may provide greater net returns than individual interventions under some production conditions, but this depends on the production system and the price of inputs (93–96). It is reported that PE pendimethalin at 2.5 kg ha^{-1} and PoE pyrithiobac sodium at 0.125 kg ha^{-1} with inter-cultivation at 60 DAS gave a net return of ₹107885 ha^{-1} (77). In another irrigated-cotton study, PE pendimethalin and PoE pyrithiobac sodium + quizalofop-ethyl (0.06 + 0.05 kg ha^{-1}) produced the highest net return (B : C ratio = 2.14) (91). Economic superiority should therefore be interpreted as context dependent.

The most common economic trend, observed across the quantitative evidence, is that if sequential control can be applied in time, then repeated manual operations can be minimised without loss of yield. In one study, pendimethalin at 1 kg ha^{-1} in combination with one hoeing achieved high net return and B : C ratio (76) and in another study, PE pendimethalin in combination with a glyphosate or a pyrithiobac sodium-based sequence resulted in high gross returns (85). Multiple seasons provide long-term IWM productivity and economic returns (34). Weed-control efficiency, yield response, application cost, labour availability, resistance risk and environment should all be considered when planning. As the conditions (cultivar, irrigation, planting density, herbicide dose and weed spectrum) differ across the studies compared in Table 4; economic and efficacy comparisons across rows should therefore be interpreted as context-dependent rather than as a ranked, universally applicable order of superiority.

Table 3. Influence of integrated weed management on cotton yield and yield attributes

Integrated weed management practice	Finding	Reference
Pendimethalin at 2.5 L ha^{-1} + intercultural operation + manual weed removal	Increased seed cotton yield of 199.4 % over unweeded plot	(88)
Pendimethalin + glyphosate (PE and PoE) + 2 HW + 2 hoeing	Higher seed cotton yield of 854 kg ha^{-1}	(25)
Integrated weed management	Increased boll production per plant (26–41.7), individual boll weight (4.4–5.1 g) and higher seed cotton yield of 3252 kg ha^{-1}	(89)
Pendimethalin at 1 kg ha^{-1} + HW (45 DAS)	Maximum seed cotton productivity of 2109 kg ha^{-1}	(90)
Pendimethalin at 2.5 L ha^{-1} + interculturing + manual weed removal	Maximum seed cotton productivity (2578 kg ha^{-1}) in 2006 and (3613 kg ha^{-1}) in 2007	(5)
Pendimethalin (PE) + quizalofop-ethyl + pyrithiobac sodium (PoE) + a single hoeing	Highest boll production per plant, cotton productivity reached 4389 kg ha^{-1}	(78)
Pendimethalin (PE) at 1.0 kg ha^{-1} + quizalofop-ethyl at 0.05 kg ha^{-1} (PoE)+ one hoeing	Enhanced sympodial branches per plant, boll number per plant and individual boll weight	(91)
Pyrithiobac sodium + quizalofop-ethyl (PoE) at 0.125 kg ha^{-1}	Higher boll production per plant, boll weight and seed cotton productivity of 2367 kg ha^{-1} compared with the weedy check	(69)
Pendimethalin (PE) *fb* quizalofop-ethyl (PoE) at 0.05 kg ha^{-1} + a single hoeing	Enhanced sympodial branching per plant, boll production per plant, boll weight and seed cotton productivity	(92)
Pendimethalin 0.5 kg ha^{-1} + oxyfluorfen (PE) 0.05 kg ha^{-1} *fb* pyrithiobac sodium 0.062 kg ha^{-1} + quizalofop-ethyl (PoE) 0.05 kg ha^{-1}	Greater seed cotton productivity and boll production per plant	(13)
Pendimethalin followed by HW	Greater boll production and seed cotton productivity	(62)
Pendimethalin 1.0 kg ha^{-1} *fb* pyrithiobac sodium 0.062 kg ha^{-1} at 25 DAS + one hoeing	Highest seed cotton yields of 1956 kg ha^{-1} in 2020–21 and 1753 kg ha^{-1} in 2021–22	(85)

HW: hand weeding; DAS: days after sowing; PE: pre-emergence; PoE: post-emergence.

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Table 4. Comparative weed control efficiency, seed cotton yield and economic return across the main herbicide and integrated weed management treatments

Treatment	WCE (%)	Seed cotton yield	Economic return	Conditions / Reference
Metolachlor alone	57	(1751.8 and 1477.3 kg ha^{-1} during 2009 and 2010)	-	Under different irrigation systems (32)
Metolachlor + glyphosate	90–95	2146.7 kg ha^{-1} (2009) 1714.8 kg ha^{-1} (2010)		
Pendimethalin (PE) *fb* pyrithiobac-sodium + fenoxaprop-p-ethyl (PoE)	86.37	2201 kg ha^{-1}	B : C = 2.58	Irrigated hybrid cotton (68)
Pendimethalin (PE) *fb* pyrithiobac sodium (PoE) + intercultivation	-	2569 kg ha^{-1}	₹107885 ha^{-1}	Bt cotton field (77)
Pendimethalin (PE) + oxyfluorfen (PE) *fb* pyrithiobac-sodium + quizalofop-ethyl (PoE)	-	Highest seed cotton yield and boll production	-	Bt cotton (13)
Pyrithiobac sodium + quizalofop-ethyl (PoE, 0.006 and 0.005 kg ha^{-1})	71.5 (60 DAS), declining to 58.0 at harvest	-	-	Bt cotton, high-density planting (62)
Two hand weedings (25 and 45 DAS)	-	Higher than PE herbicide alone	-	Nutrient-removal comparison (93)
Mechanical weeding (20, 40, 60 DAS)	-	-	Highest gross and net returns	Bt cotton (96)

WCE: weed-control efficiency; HW: hand weeding; DAS: days after sowing; PE: pre-emergence; PoE: post-emergence.

The effectiveness of IWM in achieving the highest value is not uniformly evident across all the reviewed evidence; the benefit of IWM is that it is able to balance weed suppression with crop productivity in addition to nutrient conservation and economic return. Programmes that involve a combination of residual herbicides with a specific PoE or mechanical control are normally associated with fewer control gaps, but the economic benefit relies on the cost of the treatment, labour availability, weed pressure and production environment. The decision of which IWM programme to choose should, therefore, not be based on weed suppression alone, but on the overall performance of weed control efficacy, yield response, resource conservation and profitability.

Herbicide resistance, herbicide-tolerant cotton and future research priorities

The reviewed approaches are complementary and involve trade-offs in efficacy, cost, labour requirement and resistance risk. Herbicide diversification and IWM are of the utmost importance and herbicide modes of action that are over-relied on carry a high risk of herbicide resistance (46). While the additional flexibility of PoE herbicide selection that can be gained using herbicide-tolerant cotton depends on responsible use and in combination with other non-chemical methods (46), such flexibility is a valuable trait. Documented resistance cases in the reviewed literature remain limited relative to the broader theoretical risk associated with repeated use of a single mode of action; resistance-prevention strategies discussed above (mode-of-action rotation, tank-mixing and integration with non-chemical methods) apply irrespective of whether resistance has yet been confirmed locally. Future research priorities include: systematic monitoring of herbicide resistance in dominant weed species; standardised reporting of WCE, yield and economic returns using active-ingredient dose; region-wise or cultivar-wise critical-period studies; assessment of herbicide environmental fate (leaching, runoff, residue effects and non-target impacts) (56) and crop-safety or phytotoxicity risk under Indian conditions; evaluation of sensor-based and mechanised precision weeding technologies; and studies addressing the socio-economic barriers, extension needs and likely effects of changing rainfall and temperature patterns on weed-management decisions for Indian cotton.

Conclusion

The evidence reviewed supports three separate, evidence-based recommendations. For critical-period management, weed control is most important during the early crop-growth period, commonly 30–60 days after sowing (DAS) as a composite estimate, though growers should use the locally validated critical period where available (e.g. the wider 15–60 DAS estimate reported for Tamil Nadu zero-till cotton) rather than a single fixed calendar figure. For mechanical control, two well-timed hand weeding (HW) (typically around 20–45 DAS) reliably reduce weed density and improve yield, but high labour requirement, time consumption and rising labour cost limit its wider adoption, which has increased reliance on herbicides and integrated approaches. For herbicide and integrated weed management (IWM) programmes, sequential pre-emergence (PE) and post-emergence (PoE) herbicides combined with HW, hoeing or inter-cultivation most consistently improve weed suppression, crop productivity, nutrient conservation and economic returns, particularly where weed emergence

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is prolonged or labour is scarce, although repeated use of the same mode of action raises the risk of herbicide resistance and should be managed through diversification. Beyond the technical evidence, wider adoption of these recommendations depends on addressing socio-economic barriers such as herbicide and labour cost trade-offs, farmers' knowledge of correct dose and timing and the availability of extension support. In general, this review suggests that cotton weed control should be site-specific, economically feasible and based on combinations of complementary practices rather than any single technique. Future research should focus on monitoring herbicide resistance, uniformity in reporting weed-control efficiency, yield and economics and region and cultivar-specific refinement of the critical weed-control period in Indian cotton systems.

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Authors' contributions

The first draft of the manuscript was written by GBA. SR provided guidance for overall correction and improvement. SR, TR, MB and KS assisted with literature collection and formatting. All authors have read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest

Authors do not have any conflict of interests to declare.

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None

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During the preparation of this work, the authors used Grammarly in order to correct the grammar and maintain the academic tone of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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