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Agronomic Interventions for Sustainable Weed Management in Cotton

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ABSTRACT

Cotton (*Gossypium hirsutum* L.) is a major global crop, with India being the second-largest producer. The introduction of Bt cotton has revolutionized cultivation, but weeds remain a persistent challenge to productivity. This review discusses the impact of weeds on cotton yield and explores various agronomic interventions for effective weed management. Weeds significantly reduce cotton yield by competing for essential resources such as water, nutrients, sunlight, and space. They also act as hosts for pests and diseases further diminishing crop health and fiber quality. The critical window for managing weeds in cotton lasts for 11 to 12 weeks, starting one to two weeks post crop emergence, as neglecting weed control during this time can lead to significant yield losses, ranging from 10 to 90%. Various weed management strategies are discussed, including preventive measures (e.g., clean cultivation, weed-free seeds), cultural practices (e.g., crop rotation, intercropping), mechanical methods (e.g., hoeing, inter-row cultivation), and chemical interventions (e.g., herbicides). Each method has its advantages and limitations, necessitating an integrated approach for sustainable weed management. This review concludes that an integrated weed management approach, combining multiple strategies tailored to specific agro-ecological conditions, is crucial for effective weed control in cotton. Future research should focus on weed modeling to predict weed emergence patterns and develop precise weed control thresholds. Additionally, exploring methods to enhance crop competitiveness through cultivar selection, row spacing optimization, and irrigation/fertilization management can further improve weed management outcomes in cotton production.

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Weeds pose a significant challenge to cotton (*Gossypium hirsutum* L.) production worldwide, acting as the most detrimental biotic stressor that affects crop growth, yield, and fiber quality (Gnanavel and Babu, 2008; Iqbal et al., 2020; Sreenivas, 2000; Tariq et al., 2020). Cotton's slow early growth and extended growing season, in combination with agronomic practices such as wide row spacing, make it particularly vulnerable to weed infestations (Iqbal et al., 2022; Ortiz and Bourland, 1999; Tursun et al., 2016). Weeds compete with cotton for essential resources such as water, nutrients, sunlight, and space, thereby impeding its development and productivity (Sathishkumar et al., 2021). Moreover, weeds can exacerbate pest pressure by acting as reservoirs or alternative hosts for various insects and pathogens (Hillocks, 1995).

The severity of weed infestation is often amplified by agricultural practices such as the application of fertilizers and frequent irrigation or rainfall (Kaur et al., 2018). The resulting competition for resources during critical growth stages of the cotton plant can lead to substantial yield reductions. The magnitude of these losses is influenced by multiple factors, including the weed species present, the timing of weed emergence, weed density, weed biomass, weed phenological stages, duration of competition, and the corresponding growth stages of the cotton crop (Kaur et al., 2019; Piskackova et al., 2020).

The first 11 to 12 weeks, beginning from one to two weeks after crop emergence, are critical for the competition between cotton and weeds (Bukun, 2004; Papamichail et al., 2002). If weeds are not effectively managed during this window, yield losses ranging from 10 to 90% can occur (Dogan et al., 2014). Beyond yield, weed infestations also compromise the quality of harvested lint, further diminishing the economic value of the crop.

Therefore, a comprehensive understanding of the prominent weed flora in cotton fields, their competitive mechanisms, and their impact on cotton growth and productivity is essential for successful weed management. This knowledge can be leveraged to develop strategies that enhance crop competitiveness and formulate effective, economically viable, integrated weed management programs, ultimately leading to more profitable and sustainable cotton cultivation.

LOSSES CAUSED BY WEEDS

Cotton fields experience the emergence of a wide variety of weeds, including grasses (e.g., *Dactyloctenium aegyptium* (L.) Willd., *Cynodon dactylon* (L.) Pers., *Echinochloa* sp., *Digitaria sanguinalis* (L.) Scop., *Eleusine indica* (L.) Gaertn., *Eragrostis* sp.), broadleaf weeds (e.g., *Digera arvensis* Forssk., *Amaranthus viridis* L., *Trianthema portulacastrum* L., *Euphorbia hirta* L., *Euphorbia microphylla* Lam., *Ageratum conyzoides* L.), and sedges (e.g., *Cyperus rotundus* L., *Cyperus iria* L.) (Economou et al., 2016; Kaur et al., 2019). The specific weed species present can vary depending on the environmental conditions at a specific time and location (Blaise and Kranthi, 2020).

Due to cotton's slow initial growth and wide row spacing (67.5 cm), cotton plants take a minimum of 16 weeks to achieve 90% ground cover, whereas weed species can establish full canopy closure in approximately eight weeks (Brar and Gill, 1983). This disparity in growth rates makes cotton highly vulnerable to both direct and indirect yield losses caused by weeds.

Direct losses primarily stem from competition for essential resources such as nutrients, water, light, and space (Nalini et al., 2015). Smooth pigweed (*Amaranthus hybridus* L.) extracts soil moisture from the 122 to 183 cm depth more extensively than cotton, indicating a greater impact on deep soil water reserves (Ramachandra et al., 2016). *Amaranthus palmeri* S.Wats. competes aggressively with cotton for light resources, thereby reducing light availability to the crop and contributing to significant yield losses. Research indicates that a population density of 10 *A. palmeri* plants per 9.1 m row can result in a 50% reduction in cotton biomass (Morgan et al., 2001). Research in Punjab, India, has shown that weed competition during the first 30 days after sowing can reduce cotton yield by 10.5%; this can escalate to 57% if weeds persist throughout the growing season (Thind et al., 1995). This translates to a substantial increase in seed cotton yield (from 18.9 to 30.2 q/ha) when the weed-free period is increased from 30 days after sowing to throughout the crop growing period.

Indirect losses are equally significant. Weeds can act as reservoirs for insect pests such as whiteflies (Zhang et al., 2014) and bollworms, as well as various viral and fungal diseases (Hillocks, 1995). For example, Taye (2021) found that weedy plots had the highest insect populations, with 33.7 and 28.1% of insect species present in open field and controlled conditions, respectively. Additionally, Rodrigues and Silva (2018) observed whitefly nymphs and eggs on numerous weed species, highlighting their role in pest propagation. Mealybugs, another major cotton pest, have been reported to use 108 weed species from 32 different families (Fig. 1) as host plants (Vennila et al., 2013).

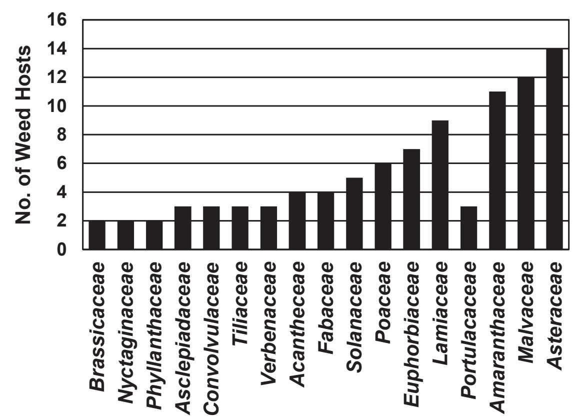

Figure 1. Families of weed host plants of mealybug in India (Source: Vennila et al., 2013).

Weeds also can interfere with the effectiveness of pesticide or plant growth regulator applications, contaminate cotton fibers during harvest, and impede harvesting operations (Tariq et al., 2020; Xie et al., 2025). These combined effects underscore the importance of implementing effective weed management strategies to mitigate yield losses and maintain the quality of cotton production.

WEED MANAGEMENT IN COTTON

Effective weed management is crucial for achieving maximum yields and net returns in cotton production. This is particularly important during the critical period of crop-weed competition, a phase when weed infestations have the most detrimental impact on yield potential. However, this critical period is often broad and poorly defined, leaving farmers unsure of the optimal timing for intervention. Delaying weed control measures can have undesirable consequences, such as allowing weed populations to double or permitting weeds to escape control and replenish the seedbank in the soil (Piskackova et al., 2020). Therefore, a thorough understanding of weed biology and ecology is essential to make informed management decisions.

Several weed management options are available, each with its own advantages and limitations. The effectiveness of each approach depends on a complex interplay of factors, including climactic conditions, soil type, the specific weed species present, other agronomic practices employed, and the quality of implementation of the chosen weed control measures.

Preventive Measures. Preventive weed management in cotton focuses on minimizing the introduction and spread of new weeds rather than controlling existing populations (Holt, 2013). This proactive approach involves several key practices, including maintaining weed-free fields through clean cultivation, using weed-free seeds and irrigation water, thoroughly cleaning agricultural machinery to prevent seed transfer between fields, using well-decomposed organic manure to avoid introducing viable weed seeds, restricting animal movement between weed-infested areas and cultivated fields, and removing weeds promptly before they produce seeds (Pala and Mennan, 2021; Zimdahl, 2018). The success of preventive weed management hinges on continuous monitoring and timely intervention to eliminate weeds before they become established. Additionally, managing weeds during the off-season, prior to cotton planting, can help reduce the incidence of insect pests and diseases that can use these weeds as hosts.

Cultural Measures. Cultural weed management in cotton focuses on creating an environment that favors the growth and competitiveness of the cotton crop while suppressing weed establishment and growth (Iqbal et al., 2020). These practices can significantly influence the dynamics of crop-weed interactions, particularly during the critical period of competition, and offer a cost-effective method to mitigate weed pressure.

A range of cultural measures can be employed, including fallow periods to deplete weed seed banks; stale seedbed techniques to encourage weed germination prior to planting and thereafter killing the same by non-residual herbicides or shallow cultivation; selecting competitive cotton varieties or hybrids; adjusting sowing time, methods, and seeding rates; implementing crop rotations to disrupt weed cycles; using cover crops to suppress weed emergence; and optimizing irrigation and fertilization practices to favor crop growth (Behera et al., 2024).

High seedling vigor in cotton can promote rapid early growth, allowing the crop to establish a dense canopy that shades out competing weeds and limits their access to resources. Studies have shown that certain cotton varieties, for example, H1226, exhibit superior seedling vigor compared to others such as H117 (Madhu et al., 2014). Additionally, intercropping cotton with cowpea in a 1:2 ratio has been demonstrated to effectively suppress weed growth due to the smothering effect of cowpea (Rajpoot et al., 2016).

In Punjab, the intra-row spacing for American cotton was widened from 45 to 75 cm to tackle issues arising from irregular rainfall patterns and increased pest infestations (Kaur et al., 2008). However, this wider spacing has inadvertently created more space for weed growth, both between rows and between plants (Narges et al., 2023). With the widespread adoption of Bt cotton and integrated pest management strategies, pest pressure has been largely alleviated. Therefore, it could be worthwhile to reconsider the optimal plant spacing to strike a balance between weed suppression and maintaining sufficient plant population for optimal yield.

Mechanical Measures. Mechanical weed control in cotton involves the use of tools such as hoes, discs, and rotary weeders to physically remove weeds by chopping, uprooting, or burying them (Kumar et al., 2022). This method begins with pre-sowing tillage and continues throughout the crop's life cycle as inter-row cultivation until the risk of damaging the cotton plants becomes too high. Mechanical weed control is particularly useful for managing weeds that have escaped herbicide treatment or developed resistance. However, it can be less effective in proximity to crop plants and can inadvertently spread weed seeds or other propagules (Hussain et al., 2018).

Deep tillage using a moldboard plow led to a 73% reduction in Palmer amaranth emergence, indicating significant suppression of weed emergence through soil inversion (Farr et al., 2022). In contrast, mechanical disturbance of the soil can create favorable conditions for weed emergence and, over time, lead to soil degradation (Chhokar et al., 2007; Franke et al., 2007). The increasing scarcity and cost of labor further limit the practicality of mechanical weed control (Abbas et al., 2018). Inter-row cultivation becomes infeasible after the cotton plants reach the square-formation stage and due to the varying emergence patterns of different weed species (Kaur et al., 2019). Therefore, mechanical weed control should be integrated with other strategies for comprehensive weed management in cotton.

Chemical Measures. Weed management through herbicides has become the most popular method among farmers due to their ease of use, high efficacy, and cost-effectiveness compared to other options. When the right herbicide is applied at the correct dose, time, and method, it can effectively control weeds, especially when applied during periods of high weed susceptibility (Hakoomat et al., 2017; Kaloumenos et al., 2005; Marimuthu et al., 2020; Sanjaykumar et al., 2024; Veeraputhiran, 2023). However, pre-emergence herbicides, such as pendimethalin, are limited in the amount of residual control they provide (Timothy and Webster, 2013) and thus, can leave late-emerging weeds unchecked. In such cases, supplementing with post-emergence herbicides and overlapping residual herbicides can provide season-long weed control (Dadari and Kuchinda, 2004; Veeraputhiran and Srinivasan, 2015). Kaur et al. (2019) investigated the efficacy of a pyrithiobac and quizalofop pre-mix for postemergence weed control in cotton. The importance of appropriate herbicide usage was highlighted in their findings: the lowest rate (75 g ai/ha) had an increase in weed density in comparison to the higher rates tested (100 and 125 g ai/ha). Pyrithiobac is primarily effective against broadleaf weed species, whereas quizalofop targets grassy weeds, and their combined use provides comprehensive, broad-spectrum weed management (Kaur et al., 2019). Table 1 provides a list of the commonly used herbicides in cotton-based systems.

Although herbicides offer numerous benefits, their use is not without limitations. Overuse can lead to environmental pollution and potential health hazards (Jabran and Chauhan, 2018; Myers et al., 2016; Stewart et al., 2001). Additionally, the efficacy of pre-emergence herbicides can be compromised in hot, dry conditions due to insufficient moisture (Yadav et al., 2017). Non-selective herbicides are limited to inter-row application, leaving weeds within the planted crop row uncontrolled. Furthermore, the continuous use of selective post-emergence herbicides with the same mode of action can increase the risk of herbicide resistance development (Knezevic et al., 2017) and weed shifts (Owen et al., 2015). Therefore, relying solely on herbicides for weed management is not advisable. In regions like Punjab, India, where glyphosate has been banned due to health concerns, alternatives like glufosinate ammonium are recommended.

INTEGRATION OF VARIOUS APPROACHES

The limitations of individual weed control methods necessitate the development of integrated weed management (IWM) strategies to effectively address weed challenges in cotton production (Dogan et al., 2014; Iqbal et al., 2020; Nichols et al., 2015). IWM, a holistic approach that combines multiple tactics, is essential for achieving both ecological and economic sustainability. By integrating various weed control measures, IWM targets both the suppression and elimination of weeds.

For example, research in Faridkot, Punjab, India has shown that application of pyrithiobac sodium at 62.5 g/ha and quizalofop-ethyl at 50 g/ha at the two- to four-leaf stage of the weed followed by one hoeing at 60 days after sowing in cotton led to higher yield attributes and yield of cotton (Singh et al., 2016). Similarly, a two-year study in Nandyal, Andhra Pradesh, India, demonstrated that a combination of pre-emergence pendimethalin applied at 1 kg/ha, followed by a directed spray of glyphosate at 1 kg/ha at the two- to four-leaf stage of the weed, and one hoeing at 50 days after sowing significantly reduced density and dry weight of weeds (Kalyani et al., 2018).

Table 1. Herbicides commonly used in cotton-based systems in India (Blaise and Kranthi, 2020)

Herbicide	Method of Application	Dose (g a.i./ha)
Paraquat	Stale seedbed/Directed spray post emergence	300-500
Glyphosate	Stale seedbed/Directed spray post emergence	1000
Pendimethalin	Pre-emergence	750-1250
Quizalofop ethyl	Early-post emergence 20-30 DAS	50
Pyrithiobac Sodium	Early-post emergence 20-30 DAS	62.5-75
Fenoxaprop-p-ethyl	Early-post emergence 20-25 DAS	50-67.5
Haloxyfop methyl	Early-post emergence 20-25 DAS	25-60

Punia et al. (2019) reported 96.9% weed control using pendimethalin followed by a directed spray of glyphosate during 2014, whereas a combination of pyrithiobac sodium followed by quizalofop-p-ethyl followed by a directed glyphosate spray achieved 83.3% control during 2015 in Hisar, Haryana, India. These findings highlight the potential of IWM strategies to optimize weed control and enhance cotton productivity.

AREAS OF FUTURE RESEARCH

To advance sustainable weed management in cotton, future research should prioritize the development of dynamic, data-driven decision tools. These should include predictive models that simulate weed emergence, growth patterns, biomass accumulation, and competition intensity under varying climatic and soil conditions. These models can help determine the optimal timing for weed control interventions. Additionally, establishing weed control thresholds, which consider economic and practical factors such as growth stage of the crop, and time of emergence of weeds with respect to crop can guide farmers in making timely decisions about weed control before infestations become problematic (Knezevic and Datta, 2015; Knezevic et al., 2002; Korres and Norsworthy, 2015).

Another promising area is the enhancement of crop competitiveness through the development of vigorous, fast-growing cotton cultivars capable of early canopy closure. Agronomic manipulations such as narrower row spacing, increased seed rates, optimized fertilizer placement, and micro-irrigation systems can synergize with cotton varietal traits to suppress weed emergence. With the increasing pressure to reduce chemical inputs, comparative long-term studies on IWM packages under diverse agro-climatic zones should be emphasized. This includes evaluating biological agents, precision mechanical tools, and sensor-based weed mapping systems. Additionally, research should explore soil health and environmental implications of different weed control strategies to align with sustainable intensification goals.

IMPLICATIONS FOR COTTON PRODUCERS

Farmers' weed management choices are driven by the need to maximize returns per unit of land and labor while minimizing risk in increasingly variable agro-climatic conditions. Most farmers prioritize cost-effective strategies and this often leads to a heavy reliance on herbicides due to their perceived ease of application and lower labor requirements. However, the overuse of chemical herbicides can lead to diminishing returns in the long term through resistance development, regulatory bans (e.g., glyphosate), and negative environmental impacts. Also, due to rising labor costs, the feasibility of mechanical methods such as hoeing is also challenged, pushing farmers to weigh short-term input costs against long-term sustainability. In this context, IWM emerges as an economically sound approach. For example, adjusting row spacing or adopting competitive cultivars can have little to no additional financial cost but can significantly improve crop competitiveness against weeds. Similarly, scheduling herbicide applications based on weed thresholds or predictive models help farmers avoid unnecessary inputs, optimizing both timing and dosage. Thus, educating farmers on the long-term economic benefits of IWM, not just in terms of yield gains but also reduced pest incidence, fewer harvest difficulties, and better lint quality, can promote more sustainable decision-making. Empowering them with tools such as weed emergence models, economic thresholds, and varietal recommendations ensure that weed control becomes an informed investment rather than a reactive expense.

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