Review Article

Effective Weed Management Strategies for Sustainable Cultivation of Sugarcane (*Saccharum officinarum* L.): A comprehensive Review

ABSTRACT

Sugarcane (*Saccharum officinarum* L.) is a significant crop in global agriculture, often referred to as "wonder cane" for its slow yet robust growth. Despite its importance, sugarcane faces a critical challenge from weed infestation, which can significantly reduce yields if not properly managed. Weed competition is most intense during the early stages of sugarcane growth, with studies indicating that unchecked weed presence during this critical period can result in yield reductions ranging from 20% to 40%. In some cases, this reduction can reach as high as 70%.This review explores effective weed management strategies for sustainable sugarcane cultivation, emphasizing the importance of controlling weeds during the early phase of crop development. Beyond this phase, the sugarcane crop tends to smother weed growth on its own. However, early and effective weed management is crucial to prevent heavy infestations that could lead to yield loss, increased harvesting costs, and other complications.The Indian Institute of Sugarcane Research (IISR) has developed "Integrated Weed Management," a technology that provides cost-effective weed control solutions for sugarcane farmers. This approach integrates various methods, including pre-emergence and post-emergence herbicide applications, hand weeding, and mechanical cultivation. Pre-emergence herbicides like atrazine and oxyfluorfen, followed by post-emergence applications of glyphosate, have proven effective in controlling weed growth in sugarcane fields. Additionally, certain weed species, such as *Paspalum paniculatum* and *P. urvillei*, can cause allopathic effects on sugarcane roots, further emphasizing the need for timely weed management.The implementation of integrated weed management techniques has shown to reduce the weed seed bank, which is crucial for sustainable sugarcane cultivation. These strategies not only ensure higher yields and reduced costs but also support the overall health of sugarcane crops by preventing the proliferation of weeds that could serve as hosts for diseases and pests.By adopting effective weed management strategies, sugarcane farmers can achieve sustainable cultivation, maximizing yield while minimizing environmental impact and ensuring a successful harvest.

Keywords: *Allopathic, Sustainable, Proliferation, Pre-Emergence, Atrazine and Oxyfluorfen*

1. INTRODUCTION

Sugarcane (*Saccharum officinarum* L.) is a crucial C4 crop in tropical and subtropical regions, representing approximately 80% of the world's sugar production and 35% of ethanol production [1]. As the second-largest producer of sugarcane after Brazil, India contributes around 430.50 million tons from 5.09 million hectares, with an annual productivity of 8.44 tons/ha [2, 78]. Given its long duration, slow initial growth, and wide row spacing, sugarcane creates a favourable environment for weed infestation, leading to significant competition for resources, affecting overall crop yield.Weed infestation in sugarcane fields is a significant issue, with potential yield losses ranging from 10% to complete crop failure [3]. Nearly 150 weed species, including annuals, perennials, and parasitic weeds, have been reported in Indian sugarcane fields [4]. The most common weeds include sedges (*Cyprus rotundus*), grasses (*Cynodon dactylon, Sorghum halepense, Imperata cylindrica*), and broadleaf weeds (*Chenopodium album, Convolvulus arvensis, Striga asiatica, Amaranthus viridis*) [5]. The critical period for crop-weed competition in sugarcane is recorded between 60-120 days after planting for spring cane and up to 150 days for autumn cane, underscoring the importance of timely and effective weed management [6].

Various approaches to weed control in sugarcane are employed, including physical, chemical, and integrated weed management (IWM) techniques [7]. Cultural practices like ploughing, hand weeding, and mulching are traditional methods but are often labor-intensive, time-consuming, and costly [8]. Chemical control with herbicides offers a more economically feasible alternative. The use of pre-emergence or post-emergence herbicides, or a combination of both, has become increasingly popular for efficient weed management in sugarcane fields [9]. Integrated Weed Management, combining physical and chemical methods, is gaining traction among farmers seeking more effective and sustainable approaches to weed control, promising higher cane yields and reduced crop-weed competition [10].

Chemical weed control in sugarcane involves the application of pre-emergence and post-emergence herbicides to manage weed populations effectively [11]. Pre-emergence herbicides are typically applied within a few days of planting to prevent weed establishment, while post-emergence herbicides are applied later to target emerging weeds [12]. Common pre-emergence herbicides include atrazine and simazine, which are effective at controlling broadleaf weeds and certain grasses [13]. Post-emergence herbicides like 2,4-D are used to target broadleaf weeds, providing extended control for 50 to 60 days [14] . For twining weeds like Ipomoea spp. and Convolvulus spp., herbicides such as atrazine and metribuzin are applied between the cane rows after earthing up. In cases where the parasitic weed Striga is a problem, additional applications of these herbicides after earthing up can effectively control its growth.

Integrated Weed Management (IWM) has gained attention as a more sustainable approach to weed control in sugarcane. IWM combines agronomic, mechanical, and chemical methods to maintain weed populations below economic thresholds while minimizing environmental impact [15]. The success of IWM relies on the strategic use of herbicides, along with hoeing and manual weeding, to reduce weed competition without affecting cane growth and yield [16]. By employing a combination of pre-emergence and post-emergence herbicides, followed by manual hoeing and earthing up, IWM has shown significant improvements in weed control efficiency and sugarcane yields. The introduction of IWM technology has resulted in increased cane yield, reduced weed density, and improved cost-effectiveness compared to traditional weed management practices [17]. As farmers adopt IWM, the sugarcane industry can benefit from enhanced productivity and sustainability.

2. TYPES OF WEEDS IN SUGARCANE

Weeds in sugarcane fields can be broadly categorized into three types: grasses, broadleaf weeds, and sedges [18]. Grasses are the most common type of weed found in sugarcane fields, characterized by their narrow leaves and fibrous root systems [19]. Common examples of grass weeds *include Paspalum urvillei,Digitaria horizontalis*, and *Cynodon dactylon*. Broadleaf weeds, on the other hand, are identifiable by their wide leaves and often rapid growth rates [20]. These include species like Solanum nigrum, *Ageratum conyzoides,* and *Chenopodium album*. Lastly, sedges, such as *Cyperus rotundus* and *Kyllinga spp.,* are distinctive for their triangular stems and robust underground structures like tubers and rhizomes. Understanding the types of weeds is crucial because different weed types may require distinct management approaches [21]. For example, grasses and sedges are often more challenging to control due to their extensive root systems, while broadleaf weeds may be more easily managed through cultural and chemical methods. Moreover, some weeds have unique growth patterns, contributing to varied challenges during different stages of sugarcane growth. A comprehensive weed management strategy in sugarcane must consider the specific types of weeds present in a given field and adopt a multi-faceted approach to control them effectively[22].

2.1 Common Weed Species in Sugarcane Fields

Several weed species are commonly found in sugarcane fields, each posing unique challenges to growers [23]. Among grass weeds, *Paspalum paniculatum* and *Cynodon dactylon* are widely prevalent, often due to their ability to spread rapidly through rhizomes and stolons [24]. These grasses can quickly take over sugarcane fields, leading to intense competition for resources like water, nutrients, and sunlight. Broadleaf weeds such as *Convolvulus arvensis, Amaranthus viridis*, and *Euphorbia hirta* are also frequently encountered in sugarcane cultivation. These species can outcompete young sugarcane plants by growing taller and shading them, hindering the crop's early development.Sedges, like *Cyperus rotundus* and *Kyllinga bulbosa,* are another common group of weeds in sugarcane fields. These species are particularly problematic because of their underground storage structures, allowing them to survive adverse conditions and re-emerge even after treatment. The presence of these common weed species underscores the importance of adopting effective weed management strategies that can address a broad spectrum of weed types [25]. Tailoring control measures to target these specific species is essential for maintaining optimal sugarcane yields and reducing the impact of weeds on crop quality.

2.2 Variability in Weed Infestations

Weed infestations in sugarcane fields can vary significantly based on several factors, including agro-climatic conditions, sugarcane variety, planting time, and cultivation practices [26]. For example, fields planted with early-maturing sugarcane varieties may experience different weed pressure compared to those with late-maturing varieties. This is because early varieties tend to initiate stalk formation sooner, which may reduce the period of vulnerability to weed competition. Additionally, climatic factors such as temperature and rainfall can influence the types of weeds that thrive in a given region, with some areas favouring grasses and others broadleaf weeds.Another aspect of variability in weed infestations is related to soil type and fertility [27]. Soils rich in organic matter may encourage the growth of certain broadleaf weeds, while sandy soils might be more prone to sedge infestations [28]. Furthermore, the frequency and timing of irrigation can also impact weed growth, with more frequent watering potentially leading to higher weed density. This variability underscores the need for flexible and adaptable weed management strategies that consider local conditions and specific weed pressures. Successful weed management in sugarcane requires a thorough understanding of these variations to develop targeted and effective control measures.

2.3 Impact of Weeds on Sugarcane Yield

Weeds can have a significant impact on sugarcane yield, both in terms of quantity and quality. When weeds are not adequately controlled, they compete with sugarcane for essential resources like water, nutrients, and sunlight [29]. This competition can stunt the growth of sugarcane, leading to reduced stalk height and fewer millable canes. As a result, the overall yield of sugarcane can decrease substantially, with studies showing that weed infestations can cause yield losses ranging from 10% to 40% or even complete crop failure in extreme cases. The critical period for weed control in sugarcane is typically within the first few months after planting, when young sugarcane is most vulnerable to competition.In addition to reducing yield, weeds can also affect the quality of sugarcane [30]. Certain weeds, like Striga asiatica, are parasitic and can directly damage sugarcane roots, affecting the plant's overall health and reducing sucrose content. Other weeds may harbor pests and diseases, which can further harm sugarcane and complicate harvesting operations. Weeds that produce dense foliage can interfere with harvesting machinery, leading to increased costs and delays. Therefore, effective weed management is crucial not only for maximizing sugarcane yield but also for ensuring high-quality cane production and smooth harvesting operations.

3. WEED CONTROL IN SUGARCANE: METHODS AND PRACTICES

Effective weed control in sugarcane cultivation is critical to maintaining high yields and reducing competition for resources [31]. Weed control methods in sugarcane include physical, chemical, Biological and cultural for integrated weed management (IWM) techniques (Figure 1), each with unique benefits and challenges. In this review, we explore the various methods used for controlling weeds in sugarcane fields and discuss the best practices for achieving optimal results.

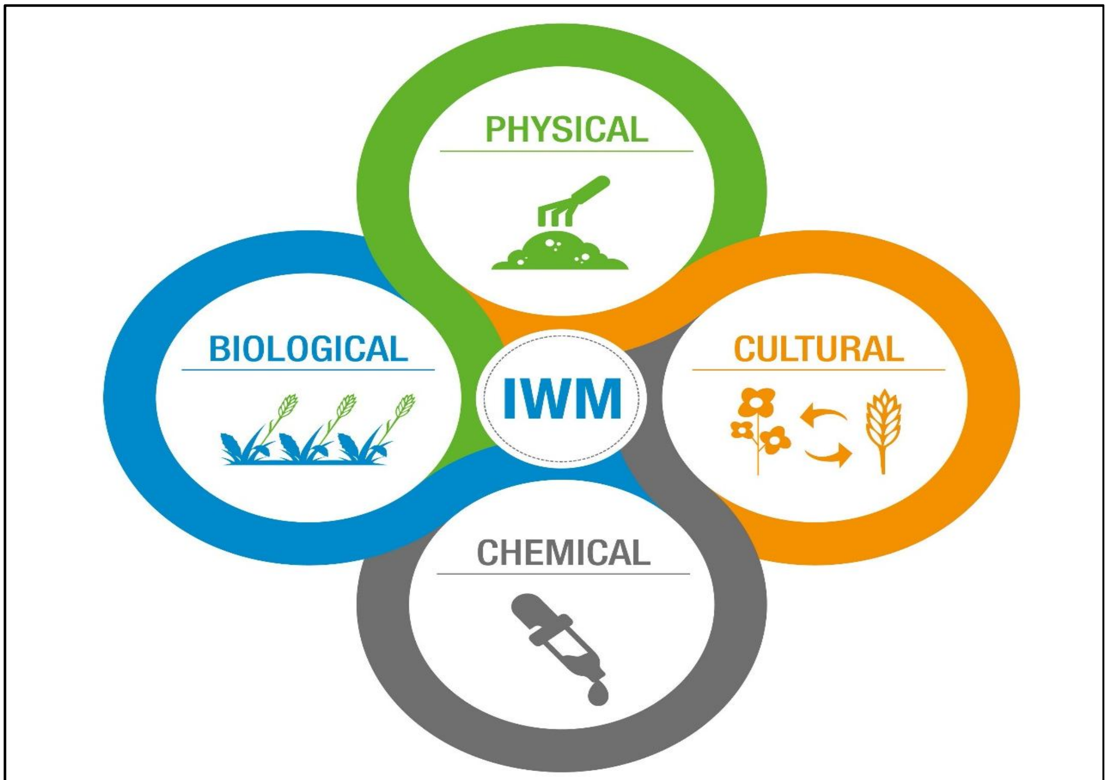

Figure 1: Integrated weed management through various methodologies

3.1 Physical Weed Control

Physical weed control in sugarcane relies on mechanical methods, such as hoeing and intercultural operations, to manage weeds during the growing season[32]. Since sugarcane is typically planted in wide rows, there is ample space for shallow-rooted weeds to grow. To combat this, farmers often perform a series of hoeing operations, usually 3-4 times, after each irrigation during the tillering phase of the crop. This approach not only helps control weed growth but also provides additional benefits by improving soil aeration and facilitating better cane root development. Physical weed control is considered a traditional method, offering a chemical-free approach to weed management [33]. It is particularly useful in the early stages of sugarcane growth, when weeds can quickly establish themselves and compete with the crop for nutrients, water, and light.

Despite its effectiveness, physical weed control has drawbacks, mainly due to the high labour costs and extensive time requirements [34]. As labour becomes more expensive and less available, farmers face increasing challenges in maintaining effective weed control through manual or mechanical means. This has prompted a shift towards more economically feasible methods, such as chemical weed control or integrated weed management, which combines physical and chemical approaches. While physical weed control remains a valuable tool in sugarcane cultivation, its limitations underscore the need for a more comprehensive weed management strategy that balances effectiveness with cost and labour efficiency [35].

3.2 Chemical Weed Control

Chemical weed control plays a pivotal role in managing weeds in sugarcane fields by using herbicides to target specific types of weeds at different stages of crop growth [36]. Pre-emergence herbicides are applied soon after planting to prevent weed seedlings from establishing and competing with the sugarcane[37]. Atrazine is a widely used pre-emergence herbicide in sugarcane cultivation, typically applied at rates ranging from 1.25 to 2.0 kg per hectare[38]. This herbicide is effective against a variety of broadleaf weeds and some grasses, providing weed-free conditions for about 50 to 60 days after application. The use of pre-emergence herbicides like atrazine reduces the need for manual weeding and allows the sugarcane to grow without significant competition during its critical growth phase.

As the sugarcane grows, post-emergence herbicides are employed to manage weeds that have emerged after the initial pre-emergence application. Herbicides like 2,4-D sodium salt, applied at rates between 1.0 and 1.5 kg per hectare, are effective in controlling a range of broadleaf weeds that can emerge later in the season [39]. These post-emergence applications are typically directed at the weeds without affecting the sugarcane plants, allowing for targeted weed control. The combination of pre-emergence and post-emergence herbicides provides an efficient approach to weed management, reducing labour costs associated with manual weeding and ensuring that sugarcane fields remain relatively weed-free throughout the growing season[40]. While chemical weed control offers significant benefits in terms of efficiency and labour savings, it's important to use these chemicals judiciously to minimize environmental impact and prevent the development of herbicide-resistant weeds.

3.3 Cultural Weed Management in Sugarcane

Cultural weed management involves practices that disrupt weed growth and competition by manipulating the growing environment. In sugarcane, this method includes techniques like crop rotation, cover cropping, mulching, and planting density adjustments [41]. Crop rotation can break the life cycles of certain weeds, reducing their prevalence in subsequent plantings [42]. By rotating sugarcane with crops that suppress specific weeds, farmers can manage weed populations without relying solely on chemical herbicides. Cover crops, such as legumes and grasses, are planted between sugarcane rows to outcompete weeds, smothering them and reducing their establishment [43]. Additionally, cover crops contribute organic matter to the soil, enhancing its structure and fertility.

Mulching is another effective cultural practice in sugarcane, where organic or inorganic materials are applied to the soil surface to suppress weeds and retain moisture [44]. Organic mulches like straw or sugarcane residues decompose over time, enriching the soil with nutrients. Adjusting planting density can also influence weed management; narrower spacing between sugarcane rows reduces the available space for weeds to grow[45]. Moreover, farmers often practice hoeing and manual weeding during the early growth stages to remove weeds and aerate the soil. These cultural practices not only reduce weed competition but also contribute to improved soil health, reduced erosion, and enhanced sugarcane growth.

3.4 Biological Weed Management in Sugarcane

Biological weed management in sugarcane relies on the use of living organisms or their byproducts to control weed populations. This approach offers a sustainable and environmentally friendly alternative to chemical herbicides. One common biological method involves the use of allelopathic cover crops, which release natural compounds that inhibit weed growth[46]. Certain legumes and grasses can suppress weed germination and growth through this mechanism. Another strategy is to introduce natural weed predators, such as insects or nematodes, that target specific weeds without harming the sugarcane crop. These biological control agents can significantly reduce weed populations and minimize the need for chemical interventions.

In sugarcane fields, biological weed management also includes the use of beneficial microorganisms that improve soil health and suppress weeds indirectly [47]. Mycorrhizal fungi, for example, form symbiotic relationships with sugarcane roots, enhancing nutrient uptake and outcompeting soil-borne weeds for resources [48]. Bio herbicides, derived from naturally occurring bacteria or fungi, can selectively target certain weeds without affecting sugarcane. Additionally, grazing animals like sheep or goats can be used in sugarcane fields to control weeds by selectively feeding on them. This practice not only reduces weed populations but also provides a source of organic matter through animal waste. Biological weed management promotes a more balanced ecosystem in sugarcane fields and reduces the reliance on synthetic chemicals, contributing to sustainable agriculture [49].

3.5Integrated Weed Management

Integrated Weed Management (IWM) combines multiple weed control methods to achieve more sustainable and effective results [50]. The approach incorporates both physical and chemical methods, allowing for a reduction in herbicide use while maintaining high weed control efficiency. A common IWM strategy includes a pre-emergence application of metribuzin, followed by hoeing and a post-emergence application of 2,4-D. This combination provides effective control of a wide range of weeds, reduces crop-weed competition, and promotes higher sugarcane yields.

The success of IWM has been demonstrated through field trials and farmer adoption. Farmers who initially had concerns about herbicide use and its potential impact on sugarcane yield were convinced of its efficacy after observing its performance in field demonstrations [51]. Application of atrazine at 1.0 kg a.i/ha after 2-3 days of sugarcane planting under moist conditions controlled weeds for 40-45 days. A second application of 2,4-D sodium salt at 60 days after planting, followed by one manual hoeing at 90 days, effectively maintained a weed-free environment [52]. These IWM practices resulted in higher sugarcane yields and have been widely adopted by farmers seeking cost-effective and sustainable weed control solutions. Effective weed control in sugarcane requires a combination of physical and chemical methods to manage weed growth and ensure profitable crop yields. Integrated Weed Management has emerged as a successful strategy, offering a balanced approach that reduces costs and environmental impact while maintaining high levels of weed control [54]. As a result, IWM has become a preferred method for farmers looking to improve sugarcane yields and achieve sustainable agricultural practices.

4. INTEGRATED WEED MANAGEMENT IN SUGARCANE

Sugarcane cultivation is prone to weed infestation due to its long duration and wide row spacing (60 to 90 cm), providing an ideal environment for weeds to grow from planting to harvest [55]. In North India, common weeds that invade sugarcane fields include *Cyperus rotundus, Echinochloaspp*., and *Saccharum* sp. among the narrow-leaved varieties, while broad-leaved weeds such as *Chenopodium album*, *Solanum nigrum*, *Convolvulus arvensis*, *Trianthema sp*., and *Digera arvensis* are also prevalent. The critical period for crop-weed competition in sugarcane occurs between 60-120 days after planting in spring cane and 150 days in autumn cane. If these weeds are not controlled during this phase, yield reductions of 20-40% are common. Traditional methods such as hoeing are effective for controlling weeds and improving soil structure but can be labour-intensive and costly due to rising wages and limited labour availability.To address these challenges, the Indian Institute of Sugarcane Research (IISR), Lucknow, developed an "Integrated Weed Management" (IWM) technology, combining chemical herbicides with traditional hoeing to manage weeds cost-effectively without compromising sugarcane yield. This technology was introduced to farmers through the Institute-Village Linkage Programme, where initial scepticism was mitigated by demonstrating the technology's success in controlling weeds without adverse effects on sugarcane growth or yield [56].

The IWM approach begins with the application of Atrazine at 1.0 kg a.i/ha with 1000 liters of water within 2-3 days of sugarcane planting under moist conditions, providing weed control for 40-45 days [57]. To manage broad-leaved weeds, a secondary application of 2,4-D Sodium Salt at 1.0 kg a.i/ha with 600 liters of water is applied at 60 days after planting. This process is followed by one manual hoeing at 90 days after planting, ensuring comprehensive weed control. Using this technology, sugarcane yield increased to 79.0 tonnes/ha, with a net return of Rs 52,530/ha—30% and 48% higher than traditional farmer practices, respectively.The adoption of Integrated Weed Management technology has not only proven effective in controlling weeds but has also significantly increased sugarcane yields and profitability for farmers. Given these positive outcomes, farmers in the area have embraced this technology, promoting its wide adoption across sugarcane-growing regions. The IWM system has become a successful model for achieving weed-free sugarcane cultivation, showcasing the benefits of integrating chemical and manual weed control strategies in modern agriculture [58].

5. WEED MANAGEMENT IN SUGARCANE: EFFECTIVE STRATEGIES FOR OPTIMAL CROP PRODUCTION

Sugarcane cultivation is prone to significant weed pressure, which can severely impact crop yield and quality if not properly managed [59]. Effective weed management requires a combination of chemical, mechanical, and cultural strategies tailored to the unique needs of sugarcane [60]. This section outlines key weeds commonly found in sugarcane fields and the various approaches to managing them, providing valuable insights for achieving optimal crop production. The major weeds that pose a challenge to sugarcane cultivation include species from different plant families, such as *Amaranthus, Brachiaria, Cyperus,* and *Convolvulus*, among others [61]. These weeds can significantly affect sugarcane growth by competing for nutrients, water, and light. To address this issue, weed management strategies often begin with a pre-emergence application of herbicides. For instance, atrazine at a rate of 1.0 kg a.i. per hectare, applied on the third day after planting (DAP), is a common pre-emergence treatment. This is often followed by post-emergence applications of glyphosate at 1.0 liter per hectare, usually around 45 DAP, to control any emerging weeds.

In addition to chemical control, mechanical methods like one-line weeding and spade digging are employed at various stages of sugarcane growth, typically at 30, 60, and 90 DAP [62]. This helps remove weeds from the crop row and maintain proper soil aeration. The use of a junior-hoe or power tiller with tynes along the ridges at 25, 55, and 85 DAP provides further weed control and promotes proper stirring of the soil. Weed management strategies must also account for specific weed issues, such as the parasitic weed *Striga*. Post-emergence application of 2,4-D sodium salt at an appropriate dosage can help control *Striga*, but caution is advised to avoid harming neighboring crops like cotton or bhendi[63]. To manage nut sedges like *Cyperus rotundus*, a pre-plant application of glyphosate at 2.0 kg per hectare with 2% ammonium sulfate, followed by a similar post-emergence treatment, is effective.

In sugarcane intercropping systems, weed control is managed through the pre-emergence application of herbicides like thiobencarb at 1.25 kg ai/ha, particularly when intercropping with crops like soybean, black gram, or groundnut [64]. This approach helps maintain a weed-free environment, promoting healthy growth and optimal yield in sugarcane fields. Overall, effective weed management in sugarcane involves a holistic approach, integrating chemical, mechanical, and cultural practices. By adopting these strategies, sugarcane growers can significantly reduce weed pressure, enhancing crop health, yield, and overall production efficiency.

All weed control treatments significantly increased the number of tillers compared to the weedy check [82]. The treatment involving Metribuzin 1.4 kg/ha as pre-emergence (PE) followed by 2,4-D 1.6 kg/ha at 45 days after ratoon initiation (DARI) recorded the highest number of tillers (205.0) and weed control efficiency, outperforming other treatments and the weedy check. This treatment exhibited an 11.6% increase in tiller numbers over the three hoeing treatment conducted at the 1st, 4th, and 7th weeks after ratoon initiation (WARI), highlighting the effectiveness of chemical weed control over manual operations. The number of tillers, panicles, and grain yield were also notably higher in this treatment compared to others, with 105.0 panicles, 74.3 grains per panicle, and overall better growth performance. The treatments with atrazine and metribuzin in combination with either 2,4-D or hoeing also showed substantial improvements in tiller numbers and weed control compared to the weedy check. Specifically, the use of atrazine 2 kg/ha as PE followed by 2,4-D 1.0 kg/ha at 45 DARI, and atrazine 2 kg/ha as PE followed by one hoeing at 45 DARI, resulted in 178.3 and 180.3 tillers respectively, indicating effective weed suppression and improved crop growth (Table 1). Overall, the study demonstrates the superior efficacy of chemical treatments, particularly the combination of metribuzin and 2,4-D, in enhancing tiller numbers and controlling weeds compared to manual hoeing, thereby supporting the use of herbicides for better crop management and yield improvement.

Table 1. Effect of different treatments on growth, yield and quality of sugarcane ratoon crop [82]

Treatment	Tiller count (x103/ha)	NMC (x103/ha)	Cane yield (t/ha)	PoL (%)	CCS (%)
Three hoeing at 1^{st}, 4^{th}& 7^{th} WARI	183.7	95.3	73.3	18.9	13.1
Atrazine 2 kg/ha as PE *fb* 2,4-D 1.0 kg/ha at 45 DARI	178.3	97.0	72.0	19.0	13.1
Atrazine 2 kg/ha as PE *fb* 1 hoeing at 45 DARI	180.3	92.3	71.3	18.8	13.0
Atrazine 1 kg/ha as PE *fb* 2,4-D 1.6 kg/ha at 45 DARI	164.3	74.0	57.6	18.9	13.1
Metribuzin 1.4 kg/ha PE *fb* 2,4-D 1.6 kg /ha at 45 DARI	205.0	105.0	74.3	18.7	13.0
Metribuzin 1 kg/ha as PE *fb* 2,4-D 1.0 kg /ha at 45 DARI	171.0	88.3	69.7	18.9	13.1
Metribuzin 1 kg/ha as PE *fb* 1 hoeing at 45 DARI	171.0	88.7	72.0	18.7	13.0
Glyphosate 0.4 kg/ha at 3 weeks stage as directed spray	147.0	72.3	54.7	18.8	13.1
Glyphosate 0.4 kg/ha at 3 weeks *fb* 1 hoeing at 60 DARI	151.7	79.0	62.0	19.1	13.3
Trash mulching in alt rows *fb* 1 hoeing at 1^{st}& 6^{th} WARI	156.7	81.7	64.7	18.4	12.8
Trash mulching between all rows	161.0	82.3	66.3	19.0	13.2
Diuron 1.6 kg/ha *fb* 2,4-D 1.6 kg /ha at 45 DARI	162.3	80.0	63.0	19.1	13.2
Diuron 1.6 kg/ha *fb* 1 hoeing at 45 DARI	166.3	82.3	66.6	19.0	13.3
Weedy check (no. hoeing and no herbicide application)	123.0	69.0	53.3	18.6	12.8
LSD (P=0.05)	14.4	8.7	7.6	NS	NS

Commercial cane sugar (CCS %)

6. WEED SPECIES AND INFESTATION LEVELS IN SUGARCANE

Sugarcane fields are prone to infestations from a variety of weed species, depending on the crop variety, season, and local agro climatic conditions [65]. Common grass weeds such as *Paspalum paniculatum, Paspalum urvillei,* and *Digitaria horizontalis* tend to proliferate in sugarcane fields harvested late in the season when temperatures are higher and conducive to their germination. Broadleaf weeds like *Ageratum conyzoides* and *Solanum nigrum* are more prevalent in fields harvested during cooler periods, which foster the growth of broadleaf species [66]. The diversity of weed species across different sugarcane fields requires a multifaceted approach to management.

The impact of weed infestation on sugarcane yield is significant, with cane yield generally decreasing as weed infestation periods increase. Conversely, longer weed-free periods contribute to higher yields [67]. This relationship has been observed across various trials and can be attributed to factors such as cropping year, crop cycle, cane variety, and agro climatic conditions. Early sugarcane varieties, which produce fewer tillers and exhibit a lower leaf area index, may reach the critical period for weed control (CPWC) earlier due to slower initial development [68]. Conversely, late varieties that grow faster and start stalk formation later are less susceptible to weed competition as they have a more efficient partitioning of dry matter into cane. Therefore, weed management practices must consider these variations to optimize crop yield and minimize the adverse effects of weed competition during critical periods.

7. FUTURE DIRECTIONS IN WEED MANAGEMENT

The evolving landscape of agriculture necessitates innovative approaches to weed management. Future directions in this field focus on integrating advanced technologies, sustainable practices, and precision agriculture to combat weed infestations in a more efficient and environmentally friendly manner [69]. Precision weed management, which uses data-driven insights to target specific areas with weed problems, is gaining traction. Techniques such as drone-based monitoring, remote sensing, and geographic information systems (GIS) allow for real-time assessment of weed infestations, enabling farmers to apply herbicides more judiciously. This targeted approach reduces chemical use, minimizes environmental impact, and lowers costs. Another emerging trend is the development of herbicide-resistant sugarcane varieties [70]. This genetic approach provides sugarcane plants with the ability to withstand specific herbicides, allowing for more effective weed control without harming the crop. This strategy can significantly reduce crop-weed competition and ensure higher yields. Additionally, biological weed control, which leverages natural predators and pathogens to suppress weed populations, is gaining attention. This approach aligns with organic farming principles and can contribute to more sustainable sugarcane production [80-81]. The focus on future directions is to enhance weed management efficiency, reduce chemical dependence, and promote sustainable agricultural practices.

8. CHALLENGES AND OPPORTUNITIES

Despite the advances in weed management, several challenges persist. Herbicide resistance in weeds is a growing concern, as repeated use of the same chemicals can lead to resistant weed strains [71]. This phenomenon can render traditional chemical control methods less effective, prompting the need for innovative approaches and new herbicides. Additionally, climate change is influencing weed growth patterns, with warmer temperatures and altered precipitation affecting weed proliferation. These changes require adaptive weed management strategies that account for shifting environmental conditions.However, these challenges also present opportunities for innovation and collaboration. The development of integrated weed management (IWM) strategies that combine chemical, cultural, and biological methods offers a promising solution [72]. IWM aims to reduce reliance on chemical herbicides and promote more holistic approaches to weed control. Collaboration between researchers, farmers, and industry stakeholders can lead to the creation of new tools and technologies for weed management [73]. For instance, robotics and automation are being explored to reduce labour costs and improve the precision of physical weed control. These emerging technologies have the potential to transform the way weeds are managed in sugarcane cultivation, offering new pathways for sustainability and resilience.

9. RESEARCH NEEDS AND INNOVATION

To address the evolving challenges in weed management, ongoing research and innovation are crucial. There is a need for continued development of new herbicides with different modes of action to combat herbicide-resistant weeds [74]. Additionally, research into alternative weed control methods, such as biological control and the use of cover crops, can provide sustainable solutions that complement traditional chemical approaches. The integration of precision agriculture tools, like drones and sensors, requires further exploration to refine their effectiveness and broaden their application in different agricultural settings.Innovation in genomics and biotechnology also holds promise for weed management. Research into the genetic basis of herbicide resistance in weeds can inform the development of new control methods and herbicide-resistant crops [75]. Genomic selection and editing technologies could lead to the creation of sugarcane varieties with enhanced resistance to specific weed species or environmental stressors. Collaborative research efforts between academic institutions, industry stakeholders, and government agencies can accelerate the pace of innovation in weed management, ultimately contributing to more sustainable and efficient sugarcane cultivation.

10. SUSTAINABILITY AND ENVIRONMENTAL IMPACT

Sustainability is at the forefront of modern agricultural practices, and weed management plays a significant role in achieving this goal [76]. Traditional chemical-based weed control can have adverse environmental impacts, such as soil contamination [79], water pollution, and harm to non-target organisms. Sustainable weed management seeks to minimize these negative effects by reducing chemical use, promoting organic practices, and incorporating biological control methods. Integrated Weed Management (IWM) emphasizes sustainability by combining multiple weed control strategies to reduce the environmental footprint of sugarcane cultivation [77].Efforts to improve sustainability also focus on reducing herbicide resistance and minimizing the risk of chemical residues in the environment. Biological control methods, such as using natural predators and pathogens to manage weed populations, can provide effective weed control with minimal environmental impact. Additionally, practices like cover cropping and crop rotation can help suppress weeds naturally, reducing the need for chemical intervention. By prioritizing sustainability, the sugarcane industry can contribute to a healthier ecosystem while maintaining high crop yields. Future research and development in weed management should continue to explore sustainable practices and their impact on the environment to ensure the long-term viability of sugarcane cultivation.

11. CONCLUSION

The sustainable cultivation of sugarcane relies on effective weed management strategies that balance productivity with environmental stewardship. Throughout this review, we have examined a range of approaches to weed control, highlighting the critical role of Integrated Weed Management (IWM) in reducing crop-weed competition and promoting sustainable practices. By combining physical, chemical, and biological methods, IWM offers a comprehensive solution to the challenges posed by weeds in sugarcane fields.Chemical weed control, with its use of pre- and post-emergence herbicides, has proven effective in managing weed infestations, but carries potential environmental risks and the challenge of herbicide resistance. Physical methods, such as hoeing and mechanical cultivation, offer a non-chemical approach but can be labor-intensive and costly. Biological weed control, which involves the use of natural predators and pathogens, represents a promising sustainable alternative.To achieve effective weed management, future efforts must focus on innovation and sustainability. This includes the development of herbicide-resistant sugarcane varieties, precision agriculture tools like drones and sensors, and the integration of cover crops and crop rotation to suppress weeds naturally. The ongoing evolution of weed management strategies underscores the need for collaboration among researchers, industry stakeholders, and farmers to create and implement solutions that support the long-term sustainability of sugarcane cultivation. Effective weed management in sugarcane requires a multi-faceted approach that addresses current challenges while embracing future opportunities. By leveraging the strengths of IWM, exploring innovative solutions, and prioritizing sustainability, the sugarcane industry can continue to thrive, providing economic and environmental benefits for generations to come.

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