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Weed management in Sugar Beet (*Beta vulgaris* L.): A comprehensive review

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Abstract

Weed infestation is one of the major biotic constraints limiting sugar beet (*Beta vulgaris* L.) productivity due to severe crop-weed competition during the early stages of crop growth. The critical period of weed competition extends up to 60 days after crop emergence, during which effective weed management is essential to minimize yield and quality losses. This review summarizes the major weed species associated with sugar beet and highlights recent advances in cultural, mechanical, biological, chemical, and integrated weed management (IWM) strategies. Particular emphasis is placed on precision agriculture technologies, including camera-guided hoeing, robotic weeding, and site-specific weed management, which enhance weed control efficiency while reducing herbicide dependence. The integration of conventional and precision-based weed management approaches offers an effective, economically viable, and environmentally sustainable strategy for improving sugar beet productivity and ensuring long-term agricultural sustainability.

Keywords: weed management, integrated weed management, herbicides, precision agriculture, mechanical weed control.

1. Introduction

Sugar beet (*Beta vulgaris* L.) is a temperate crop that performs well under warm days and cool nights. Owing to its high sucrose content (14-20%), it is widely cultivated for sugar production (Tayyab *et al.*, 2023) ^[16]. The continuous increase in global population, rapid industrialization, and expansion of international trade have resulted in a sustained rise in sugar demand, thereby highlighting the importance of sugar production worldwide. Among sugar-producing crops, sugar beet ranks second after sugarcane. According to FAO (2022) ^[8], sugar beet is cultivated on approximately 4.4 million hectares globally, producing about 253 million tonnes of roots and contributing approximately 25-30% of the world's white sugar production. Besides sugar production, sugar beet is also utilized for the production of ethanol, bioethanol, molasses, cattle feed, pulp, and pectin. Its relatively short crop duration of 5-6 months makes it an advantageous crop for cultivation. Moreover, compared with sugarcane, sugar beet requires approximately 30-40% less water and fertilizer, making it a comparatively resource-efficient crop (Tayyab *et al.*, 2023) ^[16].

Weed infestation is one of the major production constraints in sugar beet cultivation. Approximately 70% of the weed flora associated with sugar beet consists of broad-leaved weeds, whereas the remaining 30% comprises grassy weed species. Effective weed management is particularly important during the first 60 days after crop emergence, which represents the critical period of crop-weed competition in sugar beet (Gerhards *et al.*, 2017) ^[9]. The major weed species affecting sugar beet include *Chenopodium album*, *Amaranthus retroflexus*, *Galium aparine*, *Brassica napus*, and *Echinochloa crus-galli*. These weeds compete with the crop for essential resources, resulting in considerable reductions in crop growth and productivity. Therefore, the development of an effective integrated weed management (IWM) programme should consider the effectiveness of different weed control practices, weed growth stages, population dynamics, and the critical timing of control measures (Young, 2012) ^[17].

Currently, chemical weed control remains an important component of weed management in sugar beet cultivation because herbicides provide effective and economically feasible weed control, particularly during the critical period of crop-weed competition. However, recent studies have

demonstrated that integrating herbicides with mechanical and cultural weed management practices provides more effective and sustainable weed suppression compared with herbicide application alone (Abd El Lateef *et al.*, 2024) ^[1] Furthermore, increasing concerns regarding herbicide residues, environmental risks, and the development of herbicide-resistant weed populations have emphasized the need for precision-based and integrated weed management approaches that optimize herbicide use while minimizing environmental impacts (Fishkis *et al.*, 2024). Therefore, integrated weed management systems combining chemical, mechanical, and precision technologies are increasingly recommended to reduce agrochemical inputs without compromising weed control efficiency and crop productivity.

2. Weeds in sugar beet

Sugar beet (*Beta vulgaris* L.) fields are infested by a diverse weed flora, with approximately 60 weed species reported across sugar beet production regions worldwide (Bhadra *et al.*, 2020) ^[4]. Among these, broad-leaved weeds constitute nearly 70% of the total weed population, whereas grassy weeds account for approximately 30%. However, only a limited number of highly competitive weed species generally dominate sugar beet fields and cause substantial yield losses. Historically, two perennial weeds, *Agropyron repens* and *Convolvulus arvensis*, along with several annual weed species, have been recognized as major constraints in sugar beet production systems (Holm *et al.*, 1977) ^[10].

The major annual broad-leaved weeds associated with sugar beet include *Amaranthus retroflexus*, *Chenopodium album*, *Matricaria chamomilla*, *Polygonum aviculare*, *Fallopia convolvulus*, *Sinapis arvensis*, and *Stellaria media*, whereas important annual grass weeds include *Echinochloa crus-galli*, *Poa annua*, and *Setaria viridis*. Among these weeds, *Chenopodium album* is considered one of the most problematic species in sugar beet cultivation because it belongs to the same family (Chenopodiaceae) as sugar beet and has a strong competitive ability for essential resources such as nutrients, moisture, and light (Bhadra *et al.*, 2020) ^[4]. Additionally, volunteer sugar beet plants arising from root residues or seeds produced by bolting plants may become serious weed problems in subsequent cropping systems.

3. Weed control measure

Weed management strategies comprise a range of approaches that can be broadly categorized into four principal components: cultural, mechanical, biological, and chemical weed control methods.

3.1 Cultural Methods

Cultural weed management comprises agronomic interventions designed to enhance crop competitive ability and create conditions unfavorable for weed establishment. Agronomic practices, including optimum sowing time, appropriate plant population, narrow row spacing, mulching, and cover cropping, facilitate rapid canopy development and efficient resource utilization. Narrow inter-row spacing improves light interception by the crop canopy, thereby reducing photosynthetically active radiation reaching the soil surface and suppressing weed seed germination, emergence, and biomass accumulation. Consequently, competition from weeds for light, water, nutrients, and space is significantly reduced, resulting in improved crop growth and productivity (Bayat *et al.*, 2019) ^[2].

3.1.1 Crop rotation

Crop rotation is an important cultural weed management strategy that reduces the soil weed seed bank by disrupting weed life cycles and preventing the proliferation of dominant weed species. Rotating crops with contrasting growth habits, sowing periods, and management practices alters the agroecological environment, thereby reducing weed emergence, density, and biomass. In sugar beet-based cropping systems, crop rotation improves crop competitiveness, enhances yield stability and root quality, and contributes to sustainable weed suppression by reducing dependence on herbicides as part of an integrated weed management strategy (Benaragama *et al.*, 2024; Chauhan, 2023) ^[3, 5].

3.1.2 Mulching

Mulching is an effective cultural weed management practice that suppresses weed emergence by forming a physical barrier and reducing the transmission of photosynthetically active radiation (PAR) to the soil surface. It reduces weed density and biomass by limiting weed seed germination, conserving soil moisture, moderating soil temperature, and improving soil physical conditions. Additionally, mulching enhances water-use efficiency and creates favorable conditions for crop growth, thereby improving crop productivity. Consequently, mulching is considered an important component of sustainable integrated weed management.

3.2 Mechanical Weed Control

Mechanical weed control involves the physical removal or destruction of weeds using implements such as hoes, cultivators, rotary weeders, and inter-row weeders. These methods reduce weed density by uprooting, cutting, weeds thereby minimizing crop-weed competition for light, water, nutrients, and space. Recent advances in precision agriculture, including camera-guided hoes, machine vision, and artificial intelligence (AI)-based weed detection systems, have improved the efficiency and selectivity of mechanical weed control, particularly in row crops such as sugar beet (Gerhards *et al.*, 2022) ^[9].

3.2.1 Hoeing

Hoeing is one of the most effective mechanical weed control practices, which suppresses weeds through uprooting or severing, thereby reducing weed competition during the critical period of crop growth. Timely hoeing significantly decreases weed density and biomass while improving crop growth, nutrient uptake, and yield. Integration of hoeing with other weed management practices further enhances weed control efficiency and reduces dependence on herbicides (Chauhan, 2023) ^[5].

3.2.2 Robot-assisted intra-row weeding in row crops

To minimize crop yield losses and reduce reliance on manual hand weeding, robotic intra-row weeding systems enable precise weed removal near crop plants with minimal crop injury (Fennimore *et al.*, 2014; Lati *et al.*, 2016) ^[1, 14]. Equipped with machine vision, artificial intelligence (AI), and sensor-guided technologies, these systems accurately distinguish crops from weeds and perform selective intra-row weeding while maintaining crop stand and productivity. However, further field-scale evaluation is required to validate the weed control efficiency, crop safety, and economic feasibility of robotic hoes and flame weeders in direct-seeded cropping systems.

3.3 Biological weed control

Biological weed management involves the use of living organisms or their metabolites to suppress weed growth, offering an environmentally sustainable alternative to conventional weed control practices. Classical biological control relies on the introduction of natural enemies to regulate weed populations, whereas the augmentative approach involves the mass production and periodic release of indigenous biocontrol agents or the application of bioherbicides to enhance their effectiveness. In sugar beet, biological weed management has primarily focused on the use of microbial bioherbicides and natural phytotoxins for weed suppression (Bhadra *et al.*, 2020) ^[4]. Several fungal pathogens have shown potential for the biological control of problematic weed species, including *Abutilon theophrasti*, *Chenopodium album*, *Datura stramonium*, *Echinochloa crus-galli*, and *Sorghum halepense* (Cioni and Maines, 2010) ^[6]. Although biological weed control has not yet been widely adopted in commercial sugar beet production due to limitations in efficacy and field consistency, continued research on bioherbicides and microbial agents may provide sustainable and environmentally compatible weed management strategies in the future.

3.4 Chemical weed control

Chemical weed management remains one of the most effective and widely adopted strategies for controlling weeds in sugar beet, particularly during the early stages of crop establishment when the crop exhibits poor competitive ability against weeds. Timely herbicide application minimizes crop-weed competition for light, water, nutrients, and space, thereby safeguarding crop growth, root yield, and sugar accumulation. Herbicide programmes in sugar beet are generally categorized into pre-sowing, pre-emergence, and post-emergence applications based on the crop growth stage and the target weed flora. The selection of herbicides depends on weed spectrum, soil characteristics, environmental conditions, and the growth stage of both the crop and weeds. Modern sugar beet production increasingly relies on integrated herbicide programmes that combine residual and foliar-active herbicides to achieve season-long weed suppression while delaying the evolution of herbicide-resistant weed populations (May and Wilson, 2006; Gerhards *et al.*, 2022) ^[15, 9].

3.4.1 Pre-sowing and pre-emergence herbicides

Pre-sowing herbicides are primarily used to eliminate existing weed vegetation before crop establishment, thereby providing a weed-free seedbed that promotes uniform sugar beet emergence and early crop development. Non-selective herbicides, particularly glyphosate, are commonly applied prior to sowing to control emerged annual and perennial weeds under minimum tillage and conservation agriculture systems. Residual pre-emergence herbicides are applied immediately after sowing to inhibit weed germination and emergence by forming a protective herbicide layer in the upper soil profile. Their effectiveness largely depends on adequate soil moisture, soil texture, organic matter content, and appropriate application timing. Several residual herbicides, including chloridazon, metamiltron, ethofumesate, quinmerac, lenacil, clomazone, cycloate, and S-metolachlor, have been widely used in sugar beet for controlling a broad spectrum of annual broad-leaved weeds and certain grass species. Among these, metamiltron has consistently demonstrated high efficacy against problematic weeds such as *Amaranthus retroflexus* and *Chenopodium album*, significantly reducing weed density and biomass while improving sugar beet productivity (Bayat *et al.*, 2019) ^[2]. Residual herbicides also reduce the weed burden during the critical period of crop establishment, thereby

improving the effectiveness of subsequent post-emergence herbicide applications (May and Wilson, 2006; Gerhards *et al.*, 2022) ^[15, 9].

3.4.2 Post-emergence herbicides

Post-emergence herbicides are classified into two major groups based on their target weed spectrum. herbicides for the control of broad-leaved weeds and herbicides for the control of grassy weeds. A wide range of herbicides and tank-mixture combinations are available for the effective management of broad-leaved weeds in sugar beet. The major post-emergence herbicides used include chloridazon, clopyralid, desmedipham, endothall, ethofumesate, lenacil, metamiltron, phenmedipham, and triflurosulfuron-methyl (May and Wilson, 2006) ^[15]. These herbicides are commonly applied as tank mixtures to broaden the spectrum of weed control, improve herbicidal efficacy, and enhance crop selectivity. Moreover, the residual activity of several post-emergence herbicides provides extended weed suppression by reducing subsequent weed emergence, thereby contributing to improved sugar beet growth and productivity.

3.5 Integrated Weed Management (IWM)

Integrated Weed Management (IWM) is a sustainable and ecologically based approach that integrates preventive, cultural, mechanical, biological, and chemical weed control practices to maintain weed populations below the economic threshold level while minimizing reliance on herbicides. Rather than depending on a single weed control method, IWM employs complementary strategies that exploit differences in weed biology, crop competitiveness, and management practices to achieve effective and long-term weed suppression. In sugar beet, IWM typically involves crop rotation, optimum sowing time, competitive crop stands, mechanical inter-row cultivation, mulching, cover crops, and judicious herbicide use. This integrated approach improves weed control efficiency, delays the evolution of herbicide-resistant weed populations, reduces environmental risks associated with excessive herbicide use, and enhances crop productivity and economic returns. Consequently, IWM is recognized as the most sustainable weed management strategy for modern sugar beet production systems (Cioni and Maines, 2010; Kudsk and Mathiassen, 2020; Gerhards *et al.*, 2022; Chauhan *et al.*, 2024) ^[6, 12, 9, 5].

4. Conclusion

Effective weed management is essential for maximizing the productivity and profitability of sugar beet, particularly during the early growth stages when the crop is highly susceptible to weed competition. Although cultural, mechanical, biological, and chemical weed management practices each contribute significantly to weed suppression, no single method can provide effective and sustainable weed control under all production conditions. Therefore, Integrated Weed Management (IWM), which combines complementary weed control strategies, is widely recognized as the most efficient and environmentally sustainable approach. By maintaining weed populations below the economic threshold level, IWM enhances weed control efficacy, delays the development of herbicide-resistant weed biotypes, reduces environmental risks associated with excessive herbicide use, improves resource-use efficiency, and ultimately contributes to higher root yield, improved sugar quality, and sustainable sugar beet production.

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