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REVIEW ARTICLE

Redefining weed control: Effective strategies for finger millet (*Eleusine coracana*)

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Abstract

Being a significant rainfed crop with high nutritional value, Finger millet experiences a decrease in both growth and productivity due to various biotic and abiotic stresses. One important biotic stress element negatively affecting finger millet yield is weed infestation. The crop's delayed initial growth increases its susceptibility to weed infestation and increases competition for resources. *Echinochloa colona* (Jungle rice), *Cyanadon dactylon* (Bermuda grass), *Eleusine indica* (Indian goosegrass), *Cyperus rotundus* (Purple nutsedge), *Digitaria sangunalis* (Crabgrass) and *Commelina benghalensis* (Bengal dayflower) are among the prominent weed species found in finger millet cultivated lands. Effective weed control is crucial for enhancing farmers' yield and income. Various weed control strategies mitigate weed competition, including mechanical, cultural, chemical and integrated approaches. Among these, Integrated Weed Management (IWM), which combines cultural, mechanical and judicious use of herbicides, has shown promising results in enhancing weed suppression while maintaining soil health and sustainability. This review consolidates findings from recent studies and field trials to provide a comprehensive guide on weed management strategies in finger millet, aiming to improve productivity and promote environmentally sustainable practices.

Keywords

cultural; chemical; finger millet; integrated weed management; mechanical; weed management

Introduction

Finger millet, *Eleusine coracana* [L.] Gaertn., is an annual herbaceous plant extensively grown as a cereal crop in Asia and Africa's dry and semiarid regions. Finger millet is grown in Asia in India, Myanmar, Sri Lanka, Nepal, China and Japan and several African nations like Uganda, Kenya, Tanzania, Ethiopia, Eritrea, Rwanda, Zaire and Somalia (1). In different regions, finger millet is also referred to by names such as Ragi, Ragulu, Mandua and Nachani. Finger millet is widely cultivated across Indian states, including Karnataka, Andhra Pradesh, Tamil Nadu, Odisha, Maharashtra, Uttarakhand, Rajasthan, Gujarat and Goa (2). Notably, finger millet has higher productivity than other small millet, including foxtail millet, little millet, proso millet, kodo millet and barnyard millet. Finger millet has a remarkable recovery potential and can thrive with minimal water

(400 mm/year), making it an ideal crop for dryland environments (3). The crop is known for its genetic flexibility and ability to withstand extreme saline content, drought and nutrient deficit conditions (4-6).

Finger millet is essential in food security and sustainable agriculture due to its resilience and nutritional benefits. It is primarily grown by subsistence farmers and is highly valued for its rich nutrient profile, including high calcium and fibre content, making it a crucial dietary component in many regions. Its long shelf life and resistance to spoilage enhance its economic value. The crop is receiving positive attention from food scientists, technologists and nutritionists due to its advantageous qualities, particularly its potential role in combating malnutrition and preventing chronic diseases (7, 8). In recent years, there has been a growing trend in the Indian urban population towards millet consumption, driven by their recognized health benefits and government initiatives promoting millet-based diets.

Abiotic factors, including heat, drought, low soil fertility, salinity and biotic factors like fungal diseases, insect pests, weeds and bird damage, are responsible for finger millet's low average global yield. Weed invasion is one of the primary causes of the decline in finger millet productivity. At first, finger millet grows slowly, giving weeds an edge and significantly reducing productivity (9,10). Weed infestation is one of the most significant biotic stresses in finger millet, potentially reducing yields by as much as 70 % (11). Weeds possess inherent competitive strength, engaging in competition with crops for resources such as space, nutrients, moisture, light and carbon dioxide. This competition may decrease the accumulation of straw and grain (12, 13).

Given the critical impact of weed competition on yield reduction, effective weed management strategies are essential to ensure higher productivity and profitability for farmers. This review aims to consolidate knowledge of weed management approaches in finger millet, including mechanical, cultural, chemical and integrated weed control methods. This article provides insights into practical solutions for minimizing weed competition and improving crop performance by analyzing recent research findings and field studies. The information presented will aid researchers, agronomists and farmers in adopting effective weed control practices for sustainable finger millet cultivation.

Weed Flora in Finger Millet

Finger millet (*Eleusine coracana*) is often affected by diverse weed flora, which can significantly influence crop yield and quality. Understanding the weed species associated with finger millet is crucial for developing effective weed management strategies. Several researchers have conducted studies to identify the predominant weed species in finger millet fields under various environmental and agronomic conditions. Table 1 summarises these studies, highlighting the weed flora identified by researchers across multiple regions.

Critical Period for Weed Competition

Numerous factors, including crop type, season, cultivation techniques, climate and edaphic and biotic factors, significantly influence the diversity and distribution of weeds. The variety of weed species, density and dry weight directly impact crop yield loss. Effective weed management requires understanding weed ecology and biology, as their competitive abilities vary.

In finger millet, weed emergence differs among species, with some emerging early and others persisting beyond the crop's initial growth stages. The key phase for crop-weed competition has been identified between 25 and 45 DAS, while another study highlights the critical weed competition period as 20–30 days after emergence (22, 23). As shown in Fig. 1, *Echinochloa colona* and *Commelina benghalensis* emerge within the first 5-10 DAS, followed by *Eleusine indica* and *Digitaria sanguinalis*. *Cyperus rotundus*

Table 1. Major identified weeds in finger millet fields

References	Weed flora
(14)	**Grasses -** *Digiteria sangunalis*, *Echinochloa colona*, *Eleusine indica* and *Cyperus rotundus* **Broad-leaved weeds -** *Commelina benghalens*, *Celosia argentia* and *Euphorbia geniculate*
(15)	**Grasses -** *Digitaria marginata* and *Cynodon dactylon* **Sedges -** *Cyperus bulbosus* **Broad-leaved weeds -** *Trianthema portulacastrum*, *Portulaca oleracea* and *Sesamum ekamberi*
(16)	**Grasses -** *Echinochloa colona*, *Cynodon dactylon*, *Eleusine indica*, *Panicum miliacea*, *Dactyloctenium aegyptium* and *Digitaria marginata* **Sedges -** *Cyperus esculentus* and *Cyperus rotundus* **Broad-leaved weeds -** *Parthenium hysterophorus, Commelina benghalensis, Phyllanthus niruri*, *Portulaca oleracea*, *Mollugo disticha*, *Ageratum conyzoides*, *Achyranthes aspera, Amaranthus viridis, Alternanthra* spp, *Miomosa pudica*, *Sida cardifolia*, *Bidens spilosa* and *Sida acuta*
(17)	**Grasses -** *Digitaria sanguinalis* and *Cynodon dactylon* **Sedges -** *Cyperus rotundus* **Broad-leaved weeds -** *Phyllanthus niruri, Ipomoea pestigridis, Eclipta alba* and *Rhynchosia minima*
(18)	**Grasses -** *Cyperus rotundus, Eragrostis minor, Cynodon dactylon* and *Eragrostis coarctata* **Broad-leaved weeds -** *Commelina benghalensis, Tridax procumbens, Convolvulus arvensis, Amaranthus viridis, Euphorbia hirta*, *Ageratum conyzoides, Portulaca oleracea* and *Celosia argentea*
(19)	**Grasses -** *Echinochloa colona* **Sedges -** *Cyperus iria,* **Broad-leaved weeds -** *Eclipta alba, Alternanthera triandra* and *Phyllanthus urinaria*
(20)	**Grasses** - *Cynodon dactylon, Digitaria marginata* and *Echinochloa colona* **Sedges** - *Cyperus iria* **Broad-leaved weeds** - *Trianthema portulacastrum*, *Portulaca oleracea*, *Boerhavia erecta*, *Celosia argente*, *Corchorus olitorius* and *Cleome gynandra*
(21)	**Grasses -** *Dactyloctenium aegyptium* and *Digitaria sanguinalis* **Sedges -** *Cyperus rotundus* **Broad-leaved weeds -** *Commelina benghalensis*, *Celosia argentea* and *Trichoderma indicum*

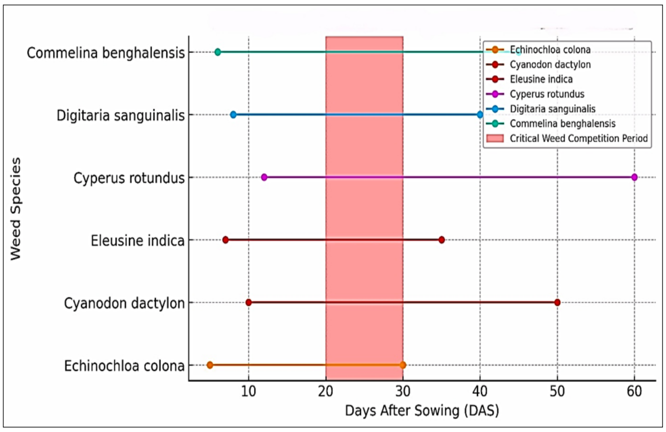

Fig. 1. Emergence pattern of major weeds in finger millet along with the critical weed competition period (20-30 DAS).

and *Cynodon dactylon* exhibit prolonged emergence beyond 30 DAS. The critical competition period (20-30 DAS) is when weed interference is most detrimental to yield, making it essential to maintain a weed-free environment during this stage. The endpoints in the graph indicate when each weed's competitive impact declines due to crop canopy suppression, natural lifecycle completion, or management practices.

Estimating yield loss due to weed infestation, which ranges from 5 % to 73 % (25, 24), is crucial for developing effective management strategies to minimize its impact and enhance productivity. Weed infestation in millets can lead to multiple forms of losses, including:

i) Direct yield reduction due to weed competition;

ii) yield decline due to reduced crop quality;

iii)Increased production costs related to harvesting, cultivation and agronomic practices; and

iv)The potential for weeds to serve as hosts for pests and disease-causing pathogens (25).

To mitigate these losses, effective weed control is crucial in reducing competition and increasing productivity (26). Research indicates that maintaining a weed-free period from 20 to 30 days after emergence is essential to prevent yield loss (23).

Weed Control Methods

Cultural methods: Cultural methods often include crop rotation, intercropping, planting density optimization and timely cultivation. By integrating cultural strategies into farming systems, growers can reduce the need for herbicides and mechanical interventions, fostering sustainable weed control practices that contribute to long-term soil health, biodiversity conservation and agricultural productivity. In the stale seedbed method, the field is prepared, irrigated and left without sowing to enable the growth of weeds, which are then eliminated using non-selective herbicides or tillage before planting and the success of this technique depends on various factors, such as the preparation technique for seed beds, the method of weed control, the species of weeds, the period of the stale seedbed and other environmental conditions (27). By planting and harvesting crops on various dates, rotating crops with varying life cycles can inhibit weed establishment and consequently, weed seed production, disrupting the formation of weed crop associations (28). The competitive advantage is given to crop varieties adjusted by planting early (29). As the crop emerges before the weeds, it prevents them from getting enough sunlight for emergence and growth (30). In a system-oriented ecological weed management plan for sustainable agriculture, growing cover crops have the potential to be an essential component (31). In addition, using organic amendments and cover crops encourages the growth of bacterial, fungal and mycorrhizal communities, which may be advantageous for crops and harmful to weeds (32). Significant effects in reducing the impact of weeds on crops can be achieved by modifying fertilizer timing, quantity and placement techniques (33). The timing of irrigation and weed control methods significantly impacted the dry weight and density of weeds (34). Applying mulch involves spreading plant matter, waste materials, or synthetic products over the soil. This widely used practice helps manage weeds by completely preventing weed seeds from sprouting or hindering the growth of new weed seedlings (35). Moreover, mulching enhances biodiversity and promotes the sustainable use of water, contributing to healthier and more resilient ecosystems (36). While cultural methods focus on altering agricultural practices to manage weed populations, mechanical methods provide a more direct approach by physically removing or damaging weeds to reduce their impact on finger millet crop.

Mechanical methods: Mechanical weed control practices constitute an essential aspect of sustainable agriculture, offering farmers effective ways to control weed populations without relying on chemical inputs. This approach involves using various tools and machinery to physically remove weeds from fields. Unlike chemical herbicides, mechanical weeding targets weeds directly, minimizing herbicide resistance risk and environmental contamination. In finger millet, two manual weeding at 30 and 45 days after sowing (DAS) and one interculture operation at 15 DAS decreased the number of weeds and their dry weight (37). Hand weeding at 20 and 30 days after sowing (DAS) significantly reduced the weed dry weight (9.4gm$^{-2)}$ and also the weed population (22.60 m^{-2}) (9). The best way to achieve optimal weed control in finger millet is to manually weed twice at 20 and 30 days after planting (DAP) (38). This will significantly boost both yield and weed control efficiency. Two hand weeding at 20 and 40 days resulted in the lowest possible overall weed dry weight of 166.00 g m^{-2} and a population of 51.00 plant m^{-2}(39). The relative dry weight of predominant monocots, dicots and overall dry weight reached the lowest values when hoeing was performed twice using a wheel hoe between rows, combined with intra-row manual weeding and two hand weedings (40). At harvest, the dry weight and minimum population were lower when hoeing twice by wheel hoe between rows and manual weeding within rows, followed by hand weeding twice, due to direct removal of weeds at 20 and 40 DAS (41). Effective weed control in conventional tillage can be achieved by triggering the germination of weed seeds (42). Also, summer tillage increased grain and straw yield harvest index and reported reduced weed density and dry matter. While mechanical methods have the chance to damage crops during weed removal, chemical weed control techniques offer a more targeted approach, minimizing the risk of crop damage and ensuring precise eradication of weeds without harming surrounding vegetation.

Chemical methods: Chemical weed management methods offer a modern solution to weed control, utilizing specialized compounds to effectively target and eliminate unwanted plants, ensuring minimal disruption to desired vegetation and agricultural productivity. In finger millet, the post-emergence herbicide application for weed control resulted in a significant reduction (21 %) in labour requirements compared to traditional intercultural operations (43). Understanding herbicide basics is crucial for their integration into weed management. Herbicides are categorized based on selectivity, mode of action and timing of application (44). Some of the herbicides and their combinations that have received recommendations from various researchers are listed in Table 2. Understanding weed-crop competition helps farmers optimize herbicide use and cultivation practices, ensuring more effective and sustainable weed management (49).

Integrated Weed Management Practices in Finger Millet

Integrated Weed Management (IWM) uses different techniques to benefit all aspects. It requires careful selection, integration and application of effective weed control methods (Fig. 2, while considering these measures' social, ecological and economic impacts. Table 3 presents the different integrated weed management practices for finger millet that various researchers have recommended in multiple studies.

Parameters employed for weed growth analysis

Weed control efficiency (53): Weed control efficiency (%) = Dry weight of weeds in weedy check plot - Dry weight of weeds in treated plot / Dry weight of weeds in weedy check plot × 100 **(Eqn. 1)**

Weed index (54): Weed Index (%) = Total yield from weed free check - Total yield from treated plot / Total yield from weed free check × 100 **(Eqn. 2)**

Weed control efficiency: Weed control efficiency measures the effectiveness of methods or treatments in reducing or eliminating weed populations in a given area. Mulching resulted in higher weed control efficiency than the un-mulched treatment (20). Specifically, rice straw mulching demonstrated superior weed control efficiency at 30 and 45 DAS. The highest weed control efficiency, reaching 99.30 %, was achieved through hoeing twice with a wheel hoe between rows and intra-row manual weeding (41). This was closely followed by hand weeding twice at 20 and 40 DAS, with an efficiency of 98.92 %. Combining Oxyflourfen at 0.25 kg ha^{-1} and hand weeding at 20 DAS gave the highest weed control efficiency of 60.18 % (14). Also, the highest level of weed-control efficiency of 82.7 % was attained with Oxyflourfen applied as pre-emergence, followed by Azimsulfuron at 20 DAT (17). The highest weed control efficiency was observed with double hand weeding, followed by the application of

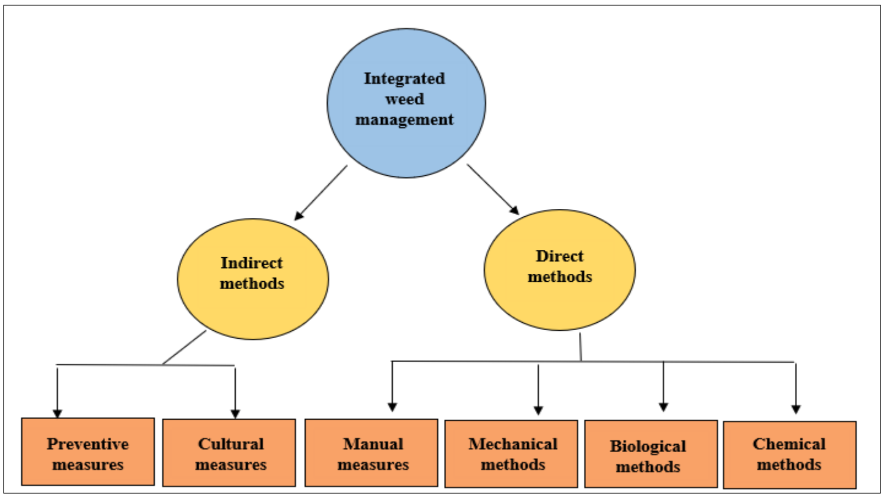

Fig. 2. Integrated weed management methods.

Table 2. Recommended herbicides and their combinations for finger millet

Herbicide	Time of application	Dominant weeds	Remarks
Isoproturon 0.5 kg ha^{-1} +2,4-D Na salt @ 0.5 kg ha^{-1}	PE + PoE	*Celosia argentea, Cynodon dactylon, Ageratum conyzoides, Panicum maxima, Alternanthera sessilis, Eleusine indica, Alternanthera triandra, Cyperus* spp.	Higher economy and grain yield (41)
Pyrazosulfuron ethyl 10 %, 20 g ha^{-1} fb Chlorimuron ethyl 10 % + Metsulfuron methyl 10 % 4 g ha^{-1}	PE + PoE	*Echinochloa colona, Cynodon dactylon, Eleusine indica, Cyperus rotundus, Parthenium hysterophorus, Commelina benghalensis, Ageratum conyzoides, Amaranthus viridis.*	Higher yield (45)
Pretilachlor @1000 g a.i. ha^{-1} fb bispyribac sodium @ 20 g a.i. ha^{-1}	PE + PoE	*Cynodon dactylon, Digitaria sanguinalis, Cyperus rotundus, Eclipta alba, Phyllanthus niruri*	Increased productivity, reduced weed uptake of nutrients (46)
Bensulfuron methyl 0.6 G @ 60 g ha^{-1} + pretilachlor 6 G at 600 g ha^{-1} fb Bispyribac sodium 10 SC @ 25 g ha^{-1}	PE + EPOE	*Cynodon dactylon, Trianthema portulacastrum, Cyperus rotundus, Eclipta alba, Dactyloctenium aegyptium, Echinochloa colona, Brachiaria mutica, Cyperus iria*	Increased yield (47)
Pendimethalin 30 EC @ 500 g a.i.ha^{-1} (3 DAS) + 2, 4-D Na salt 80WP @ 1000 g a.i.ha^{-1}	PE + PoE	*Cynodon dactylon, Eleusine indica, Echinochloa colona, Dactyloctenium aegyptium, Parthenium hysterophorus, Ageratum conyzoides, Amaranthus viridis, Commelina benghalensis, Cyperus rotundus, Cyperus esculentus.*	Increased yield (48)

PE - Pre emergence; PoE - Post emergence; EPOE - Early post emergence; fb - followed by

Table 3 . Integrated weed management strategies in finger millet

Integrated weed management strategies	Impact on crop	Reference
PE oxyfluorfen at 0.25 kg/ha + HW @ 20 and 45 DAS	Increased plant height and number of tillers	(14)
Intercultural operations @ 15 DAS + HW @ 30 and 45 DAS	Lower weed density and dry matter accumulation	(37)
PE 2,4 – D @ 0.72 kg ha $^{-1}$ + HW @ 40 DAT + inter-row spacing of 40 cm	Improved yield and low weed infestations	(39)
Oxyfluorfen (PE) fb HW @ 30 DAT	High net profit as well as B:C ratio	(23, 50)
PE pyrazosulfuron-ethyl 20 g/ha fb WHW @ 25 DAS	Highest grain yield	(51)
HW @ 20 DAS followed by inter-cultivation at 30 and 45 DAS	Increased weed control efficiency	(52)
PE bensulfuron methyl + pretilachlor at 3 kg/ha fb inter cultivation on 45 DAS		

DAS - Days after sowing; DAT - Days after transplanting; HW - Hand weeding; WHW - Wheel hoe weeding

Metsulfuron methyl + Chlorimuron ethyl ethoxysulfuron and Fenoxaprop-p-ethyl (19). Conversely, the lowest weed control efficiency was noted using Cyhalofop-butyl. The weed control efficiency of Isoproturon at a rate of 0.5 kg a.i. ha^{-1} was notably high at 25 DAS and was comparable to Bensulfuron methyl + Pretilachlor at 0.198 kg a.i. ha^{-1}(55). Similar findings were also reported in transplanted finger millet (16). Applying Pendimethalin 30 EC at a rate of 500 g a.i. ha^{-1} as a pre-emergence treatment (3 days after sowing) followed by post-emergence application of 2,4-D Na salt 80WP at 1000 g a.i. ha^{-1} (20 days after sowing) resulted in higher weed control efficiency and lowest weed dry weight (48).

Impact of Weed Control on Growth Attributes

Understanding weed management practices' influence on finger millet growth parameters is essential for optimizing crop yield and ensuring sustainable agricultural practices. Performing hand weeding in finger millet at 20 and 30 days post-transplanting led to enhanced dry weight (36.4 g plant^{-1}) and increased leaf area (990.50 cm^2 hill^{-1}) (38). Peak values for plant height (129.21 cm), leaf area index (3.21) and number of effective tillers (115.67 m^{-1}) with one hand weeding at 20 DAS followed by two inter-culture operations at 30 and 45 DAS in directly seeded finger millet (52). Research indicates the similar findings (48). Concerning herbicide treatment in finger millet, the application of pre-emergence (PE) Bensulfuron methyl + Pretilachlor at a rate of 660 g ha-1 increased plant height in transplanted finger millet (16). Oxyfluorfen as a pre-emergence treatment at 0.25 kg ha^{-1}, combined with two manual hand weeding at 20 and 45 days after sowing (DAS), led to increased plant height (97.6 cm) and number of tillers, averaging 4.6 tillers plant^{-1} (14). Applying 2,4-D at rates of both 0.5 and 0.75 kg a.i. ha -1, coupled with weeding twice at 3 and 6 weeks after sowing, resulted in the highest number of tillers (56).

Impact of Weed Control on Yield Parameters and Yield

Assessing weed management strategies' influence on yield attributes and crop yield is essential for optimizing agricultural practices and achieving maximum harvest yields. Research indicates that at harvest, the lowest dry weight and plant population (1.08 g m^{-2} and 11.55 plants m^{-2}) were found with hoeing twice using a wheel hoe between rows and manual weeding within rows. This was followed closely by hand weeding twice (1.67 g m^{-2} and 12.44 plants m^{-2}). Inter-cultivation and hand weeding at 20 and 35 DAS significantly increased grain and straw yields. This yield improvement may be linked to productive tillers, number of fingers, finger length and grain yield per plant. Applying oxyfluorfen herbicide at 0.075 kg ha^{-1} and a single manual hand, weeding operation increased the number and weight of ear heads. Pyrazosulfuron ethyl 10 % at 20 g ha^{-1} (PE) followed by Chlorimuron ethyl 10 % + Metsulfuron methyl 10 % at 4 g ha^{-1} as Post emergence (PoE), with two hand weedings at 20 and 40 DAS led to enhanced yield attributes such as number of fingers per plant, finger length (cm), number of seeds per plant (g), test weight (g), seed yield, straw yield and harvest index (%) (45, 57, 58). The highest number of fingers per square meter was observed where Pretilachlor was applied at 1000 g a.i. ha^{-1} as pre-emergence, followed by Bispyribac sodium at 20 g a.i. ha^{-1} as post-emergence (46). Research indicates the most effective strategy for achieving the highest grain yield involved applying pre-emergence Pyrazosulfuron at a rate of 20 g ha^{-1}, followed by wheel hoe weeding at 25 DAS.

Impact of Weed Control in Nutrient Uptake by Finger Millet

Various approaches to weed control profoundly affect how finger millet absorbs nutrients, ultimately shaping its growth, yield and agricultural success. The competitive behaviour of weeds for nutrients is contingent upon several factors, including weed species, growth stage, infestation severity, nutrient availability and farming practices (59). Low weed nutrient uptake was found in plots where hand weeding was done compared to other weed control strategies (60). Intra-row manual weeding at 20 and 40 days after sowing (DAS) and double wheel hoeing and intra-row manual weeding @ 20 and 40 DAS promoted greater dry matter production by optimizing nutrient, light, space and moisture utilization (61). An increase in nutrient uptake in transplanted finger millet with Bensulfuron methyl + Pretilachlor at 10 kg as pre-emergence application (16). Also, an increased nutrient uptake was noted with an application of Bensulfuron methyl at 60 g ha^{-1} combined with Pretilachlor at 600 g ha^{-1} as pre-emergence application, followed by Bispyribac sodium at 25 g ha^{-1} as early post-emergence. In sodic soils, (enhanced nitrogen, phosphorus and potassium uptake by finger millet crops with nitrogen application at 125 % of the recommended dose, pre-emergence Oxyfluorfen at 50 g ha^{-1} and early post-emergence Bispyribac sodium at 25 g ha^{-1} (62). Weed-free conditions, which were achieved by performing hoeing @ 20 and 40 DAT, applying pendimethalin @ 750 g ha^{-1} as pre-emergence, followed by Bispyribac sodium @ 20 g ha^{-1} as post-emergence recorded higher nutrient uptake. In contrast, the unweeded control treatment recorded the lowest nutrient uptake (63). Effective weed management, as observed by (51), led to enhanced nutrient uptake in finger millet, with uptake of nitrogen ranging from 43.0 % to 108.0 %, uptake of phosphorous from 3.2 % to 17.0 % and uptake of potassium from 10.6 % to 121.2 % compared to the unweeded control.

Impact of Weed Control on Nutrient Removal by Weeds

Weeds in finger millet fields can significantly impact nutrient removal, potentially affecting crop yield and soil fertility management. Fig. 3 illustrates the effect of weed-free and weedy conditions on nutrient removal by weeds, highlighting increased nutrient depletion due to weed competition in a weedy environment. Research indicates that weeds extracted 49.1 kg N, 14.0 kg P and 32.7 kg K ha^{-1} from directly sown finger millet fields, while the application of PE Bensulfuron methyl + Pretilachlor at 10 kg ha^{-1} reduced nutrient removal by weeds in drill-sown finger millet (64). Increased competition from grasses, sedges and broadleaf weeds in unweeded plots leads to increased nutrient uptake by weeds throughout the crop cycle (23). Effective weed management strategies significantly mitigated nutrient removal by weeds compared to uncontrolled conditions. Weed-free treatments exhibited no nutrient uptake by weeds, with minimal nutrient uptake observed in hoeing treatments at 20 and 40 DAT, comparable to pendimethalin at 750 g a.i. ha^{-1} as PE followed by Bispyribac sodium at 20 g a.i. ha^{-1} as PoE and pretilachlor at 1000 g a.i. ha^{-1} as PE followed by Bispyribac sodium at 20 g a.i. ha^{-1} as PoE (46). Maximum nitrogen, phosphorus and potassium uptake (19.27, 4.15 and 30.01 kg ha^{-1}) was observed with the weedy check (65, 66). Nutrient removal rates of weeds for nitrogen, phosphorus and potassium ranged from 29.2 % to 93.7 %, 40.3 % to 77.2 % and 4.0 % to 92.6 %, respectively, at 60 DAS (51).

Impact of Weed Control on Economics

Enhancing weed management strategies in finger millet farming can notably improve economic outcomes by reducing yield losses, cutting expenses and increasing market value. Herbicides offer a more cost-effective and efficient means of early-stage weed control compared to manual weeding (67). Applying Oxyflourfen at 0.25 kg ha^{-1} as PE along with one-hand weeding at 20 DAS yielded the highest benefit-cost ratio (BC ratio) of 2.07, followed by Oxyflourfen at 0.25 kg ha^{-1} as PE with two hands weeding at 20 and 45 DAS (BC ratio of 1.97) and Oxyflourfen at 0.15 kg ha^{-1} as PE with two hand weeding at 20 and 45 DAS (BC ratio of 1.89) (14). Combining Bensulfuron methyl and Pretilachlor (6.6 GR) at 0.06 + 0.60 kg a.i. ha^{-1} with one inter-cultivation at 40 DAS resulted in the highest net returns of 25193 Rs. ha^{-1} and a benefit-cost ratio 2.29 (68). The application of Ethoxysulfuron and Metsulfuron methyl + Chlorimuron ethyl yielded the highest gross returns and benefit-cost ratios, while Fenoxaprop-p-ethyl (45.0 g ha^{-1}) resulted in the lowest gross return (19). In transplanted finger millet, the highest gross return of Rs. 74508 ha^{-1}, the net return of Rs. 44572 ha^{-1} and a BCR of 2.49 with the post-emergence application of Bensulfuron methyl at 60 g ha^{-1} combined with pretilachlor at 600 g ha^{-1}, followed by early post-emergence of Bispyribac sodium at 25 g ha^{-1}was achieved. A substantial reduction in weeding costs ranging from Rs. 6810 to Rs. 6980 per hectare was reported by employing herbicides compared to manual weeding in finger millet farming (47, 69). The most favourable gross return, net monetary return and benefit-cost ratio were achieved through wheel hoe hoeing between rows, manual weeding within rows and two-hand weedings at 20 and 40 DAS (61).

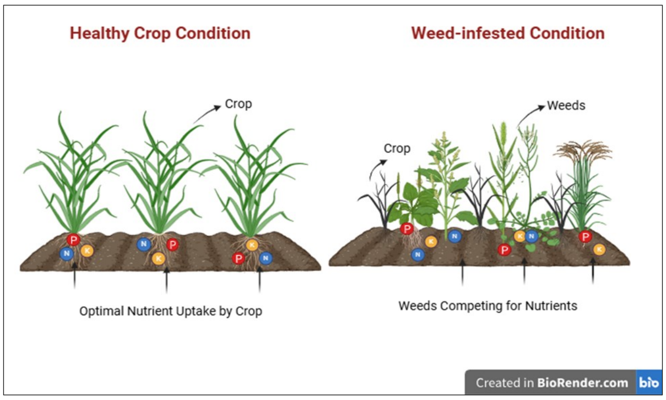

Fig. 3. Impact of weed-free vs. weedy conditions on nutrient removal by weeds in finger millet.

Future Prospects

- ◊ ***Shift toward Sustainable and integrated approaches***: Future weed management in finger millet will likely move towards more sustainable and integrated approaches due to growing environmental concerns. This shift may reduce the reliance on chemical herbicides.
- ◊ ***Reduced reliance on chemical herbicides:*** As the environmental impact of herbicides becomes more of a concern, there is a growing need for eco-friendly and effective strategies that minimize the use of chemicals while maintaining crop yields.
- ◊ ***Role of precision agriculture:*** Advances in precision agriculture will play a significant role in allowing targeted weed control measures, minimizing chemical use and optimizing crop yield.
- ◊ ***Cultural and mechanical methods:*** Cultural and mechanical weed control methods, which have traditionally been labor -intensive, may benefit from farm machinery and tools innovations. These innovations could make these methods more efficient and accessible, especially for smallholder farmers.
- ◊ ***Biological control agents and allelopathic crops:*** Increased interest in exploring biological control agents and allelopathic crops presents a sustainable solution for suppressing weed growth naturally.
- ◊ ***Breeding weed-competitive varieties:*** Breeding programs focused on developing weed-competitive finger millet varieties could reduce the need for extensive weed control measures in the long term.
- ◊ ***Collaborative research:*** Collaborative research involving agronomists, weed scientists and farmers will be essential in developing locally adapted, cost-effective and environmentally sustainable integrated weed management systems.
- ◊ ***Adaptive management Practices:*** More emphasis should be placed on adaptive management practices that evolve based on changing climate conditions, pest dynamics and farming systems. This approach will improve both weed control and the overall resilience of finger millet production systems.
- ◊ ***Holistic approach:*** A holistic approach to weed management will enhance weed control and improve finger millet farming systems' overall resilience and sustainability.

Conclusion

Effective weed management is critical in agriculture, especially considering the growing crop demand. Finger millet, mainly grown in arid and semiarid regions with scarce rainfall, presents challenges in weed control. To tackle this, integrated weed management approaches are preferred. The farming community has already implemented this approach, combining herbicide application with cultural and mechanical methods. However, exploring its continued adoption and refinement through modern technologies and innovative practices could further enhance its effectiveness and sustainability in weed management. Early-stage weed management practices like stale seedbed preparation, hand weeding and regular inter-cultivation are essential. Crop rotation, intercropping and diverse cropping systems disrupt weed life cycles, while mechanical practices like hand weeding and mulching offer alternatives to chemical herbicides. In severe cases of weed proliferation, judicious herbicide use becomes necessary. Careful herbicide selection and application and regular weed population monitoring ensure targeted and judicious weed control. Maintaining weed-free fields during critical growth stages minimizes competition between weeds and crop plants, ultimately ensuring optimal finger millet yields.

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Authors' contributions

AS and SC wrote the first draft of the manuscript and guided overall correction and improvement. AF, TK SR, RKP and PS assisted with literature collection and formatting. All authors contributed equally to revising the manuscript and approved the final draft.

Compliance with ethical standards

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