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Panoramic approach for weed management in millets

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Abstract
Millets are popular staple foods throughout Asia and Africa's semi-arid tropics. A shortfall of production and vulnerability to abiotic and biotic conditions are the primary causes of dropping millet area and productivity in India. Millets have recently been accepted as Nutri-cereals and national and international policies have offered much-needed assistance for their growth. Millets are mostly grown in rainfed and undernourished soils, resulting in them being susceptible to weed competition losses. The weed flora causes a significant reduction in millet yields of 15-97%. Weed control is vital throughout the critical period of crop-weed competition, to enhance crop productivity in semi-arid regions of India. A comprehensive analysis was done to review the suitable weed management options for millet crops under resource-poor conditions. To increase the productivity of millets relying on any single weed management technique is not a strategic option. To avoid economic loss, a combination of cultural, physical and chemical weed management strategies may successfully solve the difficulties of weed shift and resistance development in weeds, reduce the weed seed bank and control the weeds below the economic threshold level.

Keywords: Millets, weed management, yield and management

Introduction

Millets constitute the conventional primary food source of the world's dry land regions, and they have the ability to significantly contribute to food, fodder, and nutritional security in these areas. Millets are highly nutritious and climate-smart crops. These millets can be grown in dry tracts of arid and semi-arid regions due to their ability to drought tolerance. Millet grain contains high amounts of protein, fiber, essential amino acids, fatty acids, vitamins and other minerals, which led to being considered highly nutritious and Nutri cereals (Rao *et al*., 2017) [35]. They're known to have a relatively low glycemic index (GI) and thus beneficial to diabetics. Millets are classified as climate-smart crops since they are photo-insensitive, hardy, and able to endure high temperatures, in addition to being resilient to climate change. Because of their limited carbon and water footprint, they are sturdy crops. With an area of 15.48 million hectares and a yield of 12 million tonnes (Ministry of consumer affairs, food & public distribution, 2022), India is the world's largest millet grower. Rajasthan, Maharashtra, Karnataka, and Uttar Pradesh are the leading millet-producing regions in India (Adekunle *et al*., 2018) [2].

Weeds menace farmers during to cultivation of crops. There are 30,000 weed species in the globe, with 18,000 of them causing crop damage. Weeds are plants that grow in places and at times when they are not wanted. Weeds alone account for 37-45% of total losses in India (Yaduraju, 2006) [55]. These weeds also cause significant indirect damage to the productivity of crops by harbouring pests and diseases, which raise farming expenses and diminish produce quality of produce. Weeds are an essential component barrier to enhancing millet crop output, particularly during the rainy season. Millets grow slowly and are a poor weed competitor during the first several weeks. Because crop canopy development is delayed during critical periods by which weeds are well established in the soil and compete for light, soil moisture, and nutrients thereby reducing crop yields and quality (Dubey *et al*., 2023) [12]. Therefore, need-based weed management techniques would help to maximize the returns and reduce the cost of cultivation to the farmers in resource-poor conditions.

Table 1: Millets and their vernacular names

S. No.	Common name	Telugu vernacular name	Scientific name
Major millets			
1.	Sorghum /Jowar	Jonna	*Sorghum bicolor* L. Moench
2.	Bajra	Sajja	*Pennisetum glaucum* L.
Minor millets			
3.	Finger millet	Ragi or Tydalu	*Eleusine coracana* L. Gaertn
4.	Foxtail millet	Korra	*Setaria italica* L.
5.	Proso millet	Variga	*Panicum miliaceum* L.
6.	Kodo millet	Arikalu	*Paspalum scrobiculatum* L.
7.	Little millet	Samalu	*Panicum sumatrense* Roth ex
8.	Barnyard millet	Udalu	*Echinochloa frumentacea* L.
9.	Browntop millet	Andukorra	*Panicum ramose* L.

Importance of weed management in millets

Millets are relatively weak weed competitors, especially in the early phases of growth. Millets grow relatively slowly during their initial growth phase. Only when the crop reaches the mid-development stage does it have adequate canopy cover to shade the weeds and suppress their growth (Mishra, 2015) [27]. Planting in larger rows to allow for interrow cultivation and/or ditch furrow irrigation worsens the problem. Although the manual method is commonly used for weed control in millet, labour scarcity and rising labour wages have prompted farmers to investigate alternate weed management approaches. While the chemical method is the most successful for weed control in crops, it is not suggested to rely only on chemicals due to their negative influence on the environment and the development of herbicides. Therefore, a more viable approach involves integrating herbicides along with other weed management practices.

Table 2: Major weeds in millet crops

Crop	Major weeds	References
Sorghum	*Digera arvensis, Convolvulus arvensis, Amaranthus viridis, Euphorbia hirta, Alternanthera pungens, Eclipta alba, Trianthema portulacastrum, Vernonia cinerea, Physalis minima and Cyperus rotundus*	Verma *et al.*, 2018 [49]
Pearl millet	*Phyllanthus niruri, Alternanthera triandra, Cynodon dactylon, Commelina benghalensis, Panicum isachne, Amaranthus viridis, Celosia argentea* and *Cyperus rotundus.*	Girase *et al.*, 2017 [15]
Finger millet	*Digitaria marginata* Stapf, *Cyperus rotundus* L., *Ageratum conyzoides* L., *Dactyloctenium aegyptium* L. Willd., *Amaranthus viridis* L. *Celosia argentea* L., *Euphorbia hirta* L., *Alternanthera sessilis* L., *and Leucas aspera.*	Rao, 2021 [21]
Foxtail millet	*Amaranthus viridis, Commelina benghalensis Echinochloa colona, Cynodon dactylon, Sorghum halepense,* and *Celosia argentea,*	Prabhakar *et al.*, 2017 [31]
Kodo millet	*Brachiaria ramosa, Chloris barbata, Cyperus rotundus, Cynodon dactylon, Echinochloa colona, Ageratum conyzoides, Dactyloctenium aegyptium, Digitaria marginata* and *Eleusine indica,*	Lekhana *et al.*, 2021 [24]
Little millet	*Eleusine indica, Setaria glauca, Echinochloa colona, Enhinochloa crus-gulli, Amaranthus viridis, Commelina benghalensis, Phyllanthus niruri* and *Solanum nigrum.*	Chapke *et al.*, 2020 [8]

Losses due to weeds

Weeds compete effectively with crops, harbour harmful insects, and cause harvest problems (Ottman and Olsen, 2009) [29]. They compete with agricultural crops for nutrients, light, water and space, leading to significant soil nutrient losses and yield reductions. The quantity of yield loss is affected by the weed flora, the period of infestation, the soil type, the amount of rainfall, and the management practices used. Table 3 shows the yield drop in millets caused by crop weed competition. Weeds also serve as alternate hosts for millet pests and illnesses. Pathogens from several millets infect and aid overwinter weeds such as *Cynodon dactylon*, *Digitaria marginata*, *Pennisetum sp.*, *Oxalis corniculata*, and *Eragrostis tenuifolia* (Reed *et al.*, 2000) [36].

Table 3: The yield reduction in millets due to crop weed competition

Crops	Reduction in grain yield (%)	References
Sorghum	23.5–27.4%	Gharde *et al.*, 2018 [14]
Pearl millet	27.6%	Gharde *et al.*, 2018 [14]
Finger millet	72	Kujur *et al.*, 2019 [22]
Kodo millet	56.6 to 67.3%	ICAR-DWR, 2021 [18]
	55-61	Lekhana *et al.*, 2021 [24]
Little millet	59.6%	ICAR-DWR, 2021 [18]
Barnyard millet	50%	Shamina *et al.*, 2019 [37]

Crop weed competition

The weeds plants uptake higher amounts of nutrients, sunlight, soil moisture and space compared to crop plants when resources are scarce, resulting in lower yield, quality, and production costs. Allelochemicals emitted by allelopathic weeds impede the growth of new crop seedlings and cause a variety of additional problems. Fateh *et al*. (2012) [13] discovered that bindweed (*Convolvulus arvensis* L.) whole plant extract inhibited millet germination and growth characteristics. Weeds that develop alongside or before the crop are the most competitive and cause the biggest yield loss. (Swanton *et al.*, 2015) [42]. Weeds that emerge after the crop's initial growth stage are less competitive and cause fewer losses in crop yield. However, they can still pose problems if they hinder crop harvesting or reduce the quality of the economic produce. During the early growth stage of millets, the uncontrolled growth of weeds allows them to outcompete the crop by absorbing nutrients at a faster rate. Mishra *et al.* (2012) [28] observed that weeds removed about 31, 6.5 and 30 kg ha^{-1} of nitrogen, Phosphorous and potassium from control plots and also found that the following good weed control measures in sorghum crop significantly increased the nutrient uptake. Ramesh *et al.* (2019) [33] found that weeds depleted 47.7 kg of nitrogen and 31.1 kg of phosphorous in pearl millet. There was a considerable difference among the weed species in nutrient uptake. For the production of a unit quantity of Lekhana *et al.*, 2021 [24] Lekhana *et al.*, 2021 [24] dry matter, broad leaved weeds removed more amount of nutrients than the sorghum crop (Stahlman and Wicks, 2000) [38]. Millets crops were mostly cultivated in the dryland, where uncertain and dry conditions prevailed during the crop growth stages. Under moisture stress condition, weeds alone can cause 50 percent decrease in yield due to moisture stress (Abouziena *et al.*, 2014) [1].

The critical period of crop weed competition

Every crop has a crucial phase of crop weed competition, defined as the time during the crop cycle when weed control is required to avoid economic losses. Understanding the important period for weed control allows us to decide the best time to manage weeds. Weed control no longer has a substantial impact on yield once the millet crop reaches a height of about 50 cm. Weeds that emerge after this important weed-free period will have no effect on yield; nevertheless, employing management methods beyond this period will improve harvest efficiency, lower the weed seed bank, and mitigate weed-related concerns in subsequent years. Table 4 indicates the critical period for weed competition in millet crops.

Table 4: Different millet crop CPCWC during crop growth

Crops	Critical periods (DAS)	References
Sorghum	28-42	Sundari and Kumar (2002) [41]
Pearl millet	Up to 35	Thanmai *et al.* (2018) [46]
Finger millet	20-30	Pradhan and Patil (2010) [32]
Barnyard millet	25-30	TNAU (2021) [47]
Foxtail millet	20-35	TNAU (2016) [48]
Proso millet	Up to 35	TNAU (2021) [47]

Climate change and weed competition

Temperature and CO_2 changes are likely to have a significant impact on weed biology and, as a result, the dynamics of crop weed interactions. Ziska (2003) [57] investigated the impact of elevated CO_2 on the relationship between two types of dwarf sorghum (C_4) with and without the presence of a C_3 weed (velvetleaf) and a C_4 weed (redroot pigweed) and concluded that in a weed-free environment, higher CO_2 levels significantly increased sorghum leaf weight and leaf area but had no effect on seed yield or total above-ground biomass. Increased velvet leaf biomass in a consequence of rising CO_2 levels decreased production of sorghum and biomass. Similarly, as CO_2 levels rose, sorghum-redroot saw considerable decreases in seed output and total biomass.

Increased CO_2 levels were not connected with an increase in redroot pigweed biomass. These findings point to a potential increase in weedy competitiveness in a widely planted C_4 crop as atmospheric CO_2 levels rise. In another experiment, Ziska (2001) [57] discovered that as ambient CO_2 levels rise, the vegetative development, competition, and potential yield of sorghum (C_4) can be lowered by the presence of common cocklebur (*Xanthium strumarium*: C_3). Watling and Press (1997) [53] studied the effects of CO_2 concentrations (350 and 700 mol/ml) on sorghum infestation with and without Striga. They discovered that higher CO_2 concentrations led to taller sorghum plants and increased biomass, photosynthetic rates and leaf area.

Cultural methods of weed management

Good weed control is possible through the adoption of cultural methods, which are both cost-effective and easy to implement. These methods are eco-friendly and easy to operate both small and large holdings farmers, and they offer a non-chemical and ecosystem feasible approach to managing weeds. Different cultural methods are as follows.

Optimum time of sowing

By manipulating the time of sowing for a crop, either slightly earlier or later than its usual schedule, it is possible to prevent the initial flush of weeds. As highlighted by Mathukia *et al.* (2015) [26], timely weed control and timely sowing contribute to reducing crop weed competition, allowing the crop to efficiently utilize available resources, leading to enhanced growth. Das (2016) [10] found that the infestation of striga in sorghum was reduced significantly when the crop was planted very late.

Proper row spacing and method of planting

Narrow row spacing proves to be a more efficient method for suppressing weed growth compared to crops grown in wide row spacing. According to Hozayn *et al.* (2012) [16], reducing the crop row width not only enhances crop yield but also improves the crop's ability to utilize light, nutrients, and moisture more effectively. Locke *et al.* (2002) [25] observed that, faster canopy closure of the crop, reduced weed seed germination due to shading. Kaur and Singh (2006) [21] reported that paired row planting of pearl millet exhibited higher weed density and dry weight compared to regular planting. This increase in weed density in paired row planting was attributed to the wider space between two rows, which created a more favorable environment for weed germination and growth.

Plant population

According to Wu *et al.* (2010) [54], planting sorghum crops at higher densities of 7.5 plants m^{-2} resulted in a significant suppression of the growth and biomass of *Echinochloa esculenta* by 22 and 27 percent respectively, compared to lower densities of 4.5 plants m^{-2}.

Weed competitive cultivar

A crop's competitive potential is defined mostly by its ability to acquire and efficiently use critical resources such as light, moisture, nutrients, and space. Rapid emergence, biomass build up, favourable leaf features, a well-structured canopy, prolific tillering capacity, and adequate height are all qualities that increase a crop's competitive potential (Buhler, 2002). Mishra *et al.* (2015) [27] discovered that the sorghum hybrid CSH-16 outperformed the other 11 cultivars examined in terms of weed suppression. Competitive cultivars suppress weed dry matter production by absorbing light in the canopy, limiting weed light penetration.

Intercropping

When compared to solo crops, intercropping increases the usage of natural resources. Over single cropping, pearl millet + black gram (1:1) intercropping had superior weed control efficiency (65.8%), weed smothering efficiency (52.0%), and reduced weed dry weight (Mathukia *et al.*, 2015) [26]. Intercropping finger millet with small onion significantly reduced weed biomass while increasing weed control efficacy and yield (Vishalini *et al*., 2020) [52].

Crop rotation

Crop rotation involves the systematic cultivation of a sequence of different crops and crop-fallow periods on a specific plot of land. By cultivating diverse crops, various cultural practices are implemented, disrupting the growth cycle of weeds and inhibiting the proliferation of troublesome species (Barberi and Lo Cascio, 2001) [4]. In contrast, continuous mono cropping promotes the crop associated weed and can withstand the weed control methods employed, such as herbicide usage.

Soil solarisation

Soil solarisation is an easy and effective method of eliminating soil-borne pests such as weeds. It entails covering the damp soil surface with a 25 to 50 mm polyethene sheet (LDPE film) throughout the summer months to capture solar radiation. This would boost the soil temperature by 8 to 10 degrees Celsius compared to non-solarized soils, killing soilborne pests and weeds. For effective weed control, soil solarization for 4-6 weeks is required. Other benefits include improved soil structure, increased nutrient availability, particularly N, and control of soil-borne fungus. Soil solarization, according to Arora and Tomar (2012) [3], is the most effective non-chemical and agronomical weed management practise for lowering the weed seed bank.

Mulching

By covering the soil with a thick layer of mulch, weed seeds are denied the essential sunlight for germination, photosynthesis, and growth. Weed suppression via mulching was directly proportional to the amount of mulch applied, which effects light extinction through the mulch and, as a result, reduces weed seed germination (Teasdale and Mohler, 2000) [44]. Due to the physical effects of mulch, little seeded weed species tend to be more vulnerable than large seeded ones. Mulching is effective against the majority of annual weeds as well as some perennial weeds such as *Sorghum halepense* and *Cynodon dactylon*.

Stale seedbed

Stale seedbed technique is a cultural cum preventive measure. This method is based on flushing out weed seeds before crop planting to deplete the weed seed bank in the top soil layer, reducing weed occurrence (Johnson and Mullinix, 2000) [20]. It involves, creating a seedbed one or two weeks before the seed is sown in order to stimulate the emergence of weeds prior to seeding. Emerged weeds are then destroyed by cultivation or application of a non selective herbicide. Patil *et al.* (2013) [30] reported that the stale seedbed technique followed by inter cultivation twice at 20 and 35 DAP significantly reduced the weed density and weed dry weight in finger millet.

Application of natural or synthetic stimulants

Striga germination and haustoria formation depend on chemical signals from host roots. Natural stimulants like "strigol and strigol acetate" were first discovered in cotton roots, and synthetic analogues like GR 45 and GR 7 can also stimulate germination. Applying synthetic analogues before crop sowing induces striga germination, but seedlings die without a suitable host (suicidal germination). Surviving striga plants can be managed through manual weeding or contact herbicide application. Das (2016) [10] found that pre plant incorporation of GR 45 and GR 7 at 0.1-1.0 kg ha^{-1} reduced 50% of striga population in sorghum, and ethylene treatment resulted in a 90% reduction in striga seed bank in the plough layer soil.

Fertilization

Scientific manipulation of the crop weed environment through fertilizer application can stimulate crop growth and suppress weeds. Chavan *et al.* (2017) [9] found higher weed dry weight with 100 kg N ha^{-1}, while lower nitrogen levels resulted in better weed control efficiency. Split application of N also reduced weed density and dry weight. Tadesse *et al.* (2018) [43] reported a 49.8% reduction in striga density with N application up to 46 kg ha^{-1} compared to the control.

Catch cropping

Crops which stimulate the weed parasite to germinate and themselves get parasitized are called catch crops. Striga plants should be ploughed and buried along with the crop in to soil, well before they come to flowering and set seed. Growing Sudan grass just for 5 weeks and incorporating it into the soil and sowing sorghum in the stubbles reduced the infestation of *Striga hermonthica* in East Africa (Das, 2016) [10].

Allelopathic weed management

Allelopathy occurs when one live organism affects another by the emission of allelochemicals. Weed control involves manipulating a crop's allelopathic potential in order to lessen crop weed competition. Allelochemicals are released by a variety of activities, including evaporation, leaching, root leakage, and plant death, and they affect germination, growth, nutrient intake, cell division, enzyme activity, and other processes. Inhibited germination, reduced root and shoot growth, necrosis of root tips, and diminished reproductive capacity are all obvious impacts on plants (Bhadoria, 2011) [5]. Allelopathic cover crops, allelopathic intercrops, rotating with allelopathic crops, and employing allelopathic plant residues as mulches, according to Jabran *et al*. (2015) [19], are critical for weed management in sustainable agricultural systems.

Sorgoleone, an allelochemical released by the root hairs of sorghum, was found to be phytotoxic to broad leaved weeds and grasses at concentrations as low as 10 mol/L (Yang *et al.* 2004) [56]. *Setaria viridis, Amaranthus retroflexus* and *Chenopodium album* were all affected by water extracts of foxtail millet leaves and stems (Dong *et al*., 2020) [11].

Physical methods of weed management

It is one of the oldest and the most common method of weed control in millets. Different methods of physical methods of weed control are as follows:

Tillage

The primary tillage effect on weeds is mostly determined by the type of implement used and the depth of tillage. These parameters influenced the dispersion of weed seeds and propagules throughout the soil profile, which in turn determined the quantity of weeds that developed. In a rainfed pigeon pea + finger millet cropping system, conventional tillage led in deeper planting of weed seeds and a considerable reduction in weed density (Vijaymahantesh *et al*., 2013) [50].

Hoeing

Hoeing is a post planting operation that loosens and aerates the soil. It effectively controls annual weeds but may not be as effective against perennial weeds. Line sowing was a prerequisite for hoeing. Among the weed management practices, significantly lower density, dry matter of weeds, higher weed control efficiency and lower weed index were noticed in hoeing twice by wheel hoe between the rows in finger millet (Kujur *et al*., 2018) [23].

Manual weed control

Hand hoeing in the most common and efficient method of weed control in millets and age old practice. Though effective, it is time consuming, labour intensive and often costlier than the chemical method of weed control. It effectively controls annual weeds, but not perennial weeds. Among the various weed management practices, hand weeding twice at 20 and 40 DAS recorded the highest grain yield and the lowest weed index in pearl millet (Thanmai *et al.*, 2018) [46].

Chemical method of weed management

Herbicide control has been viewed as the simplest way of weed management. While numerous herbicides have been tested for weed management in sorghum, recommendations for chemicals in other millets, particularly small millets, have been limited. Atrazine has long been used as a pre-emergence pesticide to suppress weeds in millets. Ramesh *et al.* (2019) [33] discovered that applying pretilachlor (450 g ha^{-1}) pre-emergence on 3 DAS, followed by one-hand weeding on 30 DAS, dramatically reduced weed density and dry weight. Vinothini and Arthanari (2017) [51] observed in another study that a pre-emergence treatment of isoproturon (750 g ha^{-1}) followed by hand weeding at 40 DAS considerably reduced the density of weed species in irrigated Kodo millet.

Table 5: Herbicides recommended for millet crops

S. No	Crop	Herbicide	Dosage (kg ha^{-1})	Time of application	Source
01	Sorghum	Atrazine	0.75-1.0	Pre-emergence	Mishra, 2015 [27]
		Pendimethalin	0.75-1.0	Pre-emergence	
		Atrazine + pendimethalin	0.75+0.75	Pre-emergence	
02	Bajra	Atrazine	0.5	Pre-emergence	Mishra, 2015 [27]
03	Foxtail millet	Pretilachlor	500 g/ha	Pre-emergence	Sravani *et al.*, 2021 [39]
04	Finger millet	Oxadiazone	1.0	Pre-emergence	Mishra, 2015 [27]
		Butachlor	0.75	Pre-emergence	Mishra, 2015 [27]
		Bensulfuron-methyl + pretilachlor	1.0	Pre-emergence	Mishra, 2015 [27]
		Oxadiargyl fb Ethoxysulfuron	0.08 fb 0.012	3 DAS fb 30 DAS	Shubhashree, and Sowmyalatha (2019) [40]
05	Kodo millet	Isoproturon	0.50	Pre-emergence	Mishra, 2015 [27]
06	Proso millet	Atrazine	0.28-0.56	Pre-emergence	Mishra, 2015 [27]
07	Barnyard millet	Bensulfuron-methyl + pretilachlor	495 g *a.i.* ha^{-1}	Pre-emergence	Thambi *et al.*, 2021 [45]

Future Way forward

Millet cultivation is gaining popularity as "Nutri-cereals," particularly in arid and sub tropical regions, owing to their climate resilience and suitability for conventional or organic/natural farming systems. Despite their potential, millet productivity remains low and requires improvement through the hoarsening of better genetically potential varieties and enhanced management practices. Weeds pose a significant biotic constraint during millet cultivation, competing for essential resources and presenting challenges during the early growth stages. Minor millets, in particular lack selective herbicides, adding to the complexity of weed management.

In this context, an integrated weed management approach proves ideal, combining weed competitive varieties, agronomic manipulation, cultural and mechanical interventions, and judicious herbicide use. However, cautious monitoring is essential to prevent weed resistance to herbicides with the cultivation of resistant varieties.

Conclusion

Millets farming areas in India are semi-arid to arid in climate. Weeds mostly reduce crop output, which ranges from 15 to 97% depending on management practises. It is not a strategic option to boost millet productivity by depending on a single weed management approach. A mix of cultural, physical, and chemical weed management measures may successfully handle the problems of weed shift and resistance development in weeds, reduce the weed seed bank, and control the weeds below the economic threshold level.

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