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Review and outlook of weed management in millets

Ashirbachan Mahapatra[1], Rajesh Shriram Kalasare[1]*, Jnana Bharati Palai[1], Swarnali Duary[1], Chandrasekhar Sahu[2], Dwity Sundar Rout[3]

[1]Department of Agronomy and Agroforestry, Centurion University of Technology and Management, R. Sitapur, Odisha, India.
[2]Department of Biochemistry and Crop Physiology, Centurion University of Technology and Management, R. Sitapur, Odisha, India.
[3]Department of Agricultural Extension Education, Centurion University of Technology and Management, R. Sitapur, Odisha, India.

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ABSTRACT

Since ancient civilization millets have been traditionally cultivated as a staple food in Asia and Africa. After the popularization of fine cereals such as rice and wheat, the millets lost their popularity and remained confined to a limited area and production. However, when we talk about nutritional security, millets have immense potential as they are rich in different amino acids, vitamins, and minerals. Therefore, they are considered "Nutri-Cereals." Nature has also equipped them with a high potential to thrive well in resource constraint situations. Hence, considering the growing ill effects of changing climatic scenarios, their demand is going to be high in the future. As far as the cultivation of millets is considered, their yield is compromised by several biotic and abiotic stresses. Among the biotic stresses, weed infestation is one of the most important ones, which drastically reduces the yield of millets. Millets are slow growers at the early stages of their growth. Hence, if proper and timely weed management strategies are not taken then weeds deprive the crop of different growth resources such as nutrients, soil moisture, light, and space which ultimately hamper the yield. Several weed management strategies, namely, pre-emergence herbicides, and herbicide mixtures have been standardized for weed control in millets. However, limited kinds of literature are available suggesting the weed management options in millets, post-emergence herbicide options, and integrated weed management options. Post-emergence herbicides along with other methods of weed control can provide a season-long competition-free environment to the millet crops which will increase millet productivity. The available weed management options from different works of literature have been discussed in this article.

1. INTRODUCTION

The first green revolution in our country was concerned with food security, whereas the second green revolution will be concerned with nutritional security. Millets are the most important component of the nutritional security program, which are therefore called "Nutri-Cereals." Millets have been cultivated for more than 5000 years in many parts of Asia and Africa [1]. In addition to being a staple diet in Northern Africa for thousands of years, millets were also popular in China and India before fine cereals such as rice and wheat gained widespread. They are among the earliest cultivable food grains that humans have been able to identify. Sorghum (*Sorghum bicolor*), pearl millet (*Pennisetum glaucum*), finger millet (*Eleusine coracana*), foxtail millet (*Setaria italica*), little millet (*Panicum sumatrense*), barnyard millet (*Echinochloa frumentacea*), kodo millet (*Paspalum scrobiculatum*), and proso millet (*Panicum miliaceum*) which are minor cereals of the small seeded-grass family (Poaceae) mainly grown in semi-arid regions [2]. These have amazing nutritional value and are 3 to 5 times more nutritious than rice and wheat in terms of protein, minerals, and vitamins. They also have a short growing season (70–80 days), are well suited to multiple cropping systems under both irrigated and rainfed conditions, and can survive in unusually infertile soil [3-5]. Within a short time, they can offer highly desired nutrients in the form of grain and fodder. They are also known as "famine reserves" because to their improved capacity under normal storage circumstances.

Despite all the amazing qualities and capacities of millet farming systems, the area and production of millets in the country have been drastically reduced over the past five decades from 1955–56 to 2013–14. Over the past six decades from 1950–51 to 2011–12, the contribution of millets in total food grain production of the country declined from 22.17% to 6.94%. Out of many factors for the declination of millet production in the country, weed infestation is one of the most important factors. The growth of millets is slow at first and they are weaker than weeds in crop-weed competition in the first few weeks of their growth. Weeds compete for different growth resources, namely, nutrients, soil moisture, light, and space. with the crop and the competition starts when the growth resources fall below their combined demand. Due to the slow growth of millets

*Corresponding Author:
Rajesh Shriram Kalasare,
Department of Agronomy and Agroforestry,
Centurion University of Technology and Management, Odisha, India.
E-mail: rajesh.kalasare @ cutm.ac.in

in the first few weeks, their canopy growth does not occur abundantly up to mid-season and till then weeds become sufficiently established to suppress the crop. Recommended wider spacing for inter-row cultivation and furrow irrigation in millets also helps the weeds to thrive well. An improved package of practices such as nutrient and irrigation management warrants more emphasis on weed management, otherwise, weeds will take the advantage of costly inputs rather than the crop cultivated in the field. Improved weed management can only save the crop from severe weed infestation enhancing the productivity of millets. In this article, emphasis has been given to different weed flora composition and their management in millets.

2. WEED FLORA COMPOSITION

Diversified weed flora of grasses, sedges, and broad-leaved weeds (BLWs) have been noticed under different agro-climatic conditions in India which is shown in Table 1.

3. CROP-WEED COMPETITION AND LOSSES DUE TO WEED INFESTATION

Weeds compete with the crop for different growth resources when there is a limitation in their availability. Millets are slow growing in nature during the first few weeks of crop growth, and hence, they do not acquire sufficient canopy growth and weed smothering ability which facilitates the weeds to be established till mid-season of the crop. The losses from weed infestation in millets include (i) direct yield loss from lower crop quality; (ii) indirect yield loss from reduced crop quality; (iii) higher cost of harvesting, cultivation, and agronomic activities; and (iv) weeds' capacity to shelter insect pests and disease pathogens [11]. The first 4–6 weeks of crop growth are the most crucial times for crop-weed competition in the majority of millets. Tables 2 and 3 show, respectively, the millets' key crop-weed competition time and yield losses brought on by weed infestation in millets. However, yield compromising capabilities of weeds in millets differ from situation to situation depending on the crop cultivar, the aggressive nature of weeds, spacing of the crops, duration of the weed infestation, environmental conditions, and management practices. The indirect loss due to weed infestation is that weeds harbor insect pests and diseases as alternate hosts which affect the crop [12]. Weeds, namely, *Panicum repens*, *Setaria intermedia*, *Brachiaria distachya*, and *Cyperus rotundus* can act as alternate host for sorghum shoot fly [13], whereas *Echinochloa colona* can harbor *Sporisorium sorghi* which causes sorghum covered smut [14].

Table 1: Major weed flora of millets in different states of India [6-10].

States	Grasses	Sedges	BLWs
Andhra Pradesh	*Echinochloa colona, Cynodon dactylon*	*Cyperus rotundus*	*Celosia argentea, Euphorbia geniculata, Commelina benghalensis, Euphorbia hirta, Corchorus olitorius, Digera arvensis*
Bihar	*Dactyloctenium aegyptium, Echinochloa colona, Cynodon dactylon*	*Cyperus rotundus, Fimbristylis diphylla*	*Leucas aspera, Amaranthus viridis, Canabis sativa, Fumaria parviflora, Trianthema portulacastrum, Ageratum conyzoides*
Gujarat	*Cynodon dactylon, Echinochloa colona, Echinochloa crus-galli*	*Cyperus rotundus, C. esculentus, Eragrostis major*	*Chrozophora rottleri, Convolvulus arvensis, Digera arvensis, Corchorus aestuans*
Haryana	*Paspalum paspaloides, Echinochloa colona, Dactyloctenium aegyptium*	*Cyperus rotundus*	*Alhagica melorum, Celosia argentea, Trianthema portulacastrum*
Himachal Pradesh	*Digitaria sanguinalis, Panicum dichotomiflorum, Echinochloa colona, Brachiaria ramosa*	*Cyperusiria*	*Oxalis latifolia, Ipomoea purpurea, Ageratum conyzoides, Commelina benghalensis*
Karnataka	*Cynodon dactylon, Chloris barbata, Dactyloctenium aegyptium, Eleusine indica, Echinochloa colona, Digitaria marginata*	*Cyperus rotundus, Cyperus esculentus*	*Commelina benghalensis, Cinebradidema, Euphorbia hirta, Syndrella nodiflora, Borreria articularis, Celosia argentea, Ageratum conyzoides, Alternanthera sessilis, Amaranthus viridis, Amaranthus spinosus*
Madhya Pradesh	*Cynodon dactylon, Echinochloa colona, Echinochloa crusgalli, Saccharum spontaneum*	*Cyperus rotundus*	*Amaranthus viridis, A. spinosus, Commelina benghalensis, Eclipta alba, Phyllanthus niruri, Leucas aspera*
Maharashtra	*Cynodon dactylon, Echinochloa colona, Brachiaria eruciformis*	*Cyperus rotundus*	*Celosia argentea, Striga asiatica, Commelina benghalensis, Sonchus arvensis, Striga asiatica*
Odisha	*Echinochloa colona, Ischenedespaire, Digitaria ciliaris, Paspalum scrobiculatum*	*Cyperusiria*	*Ageratum conyzoides, Cyanotis*spp.*, Celosia argentea*
Punjab	*Sorghum halepense, Digitaria ciliaris, Eleusine aegypticum*	*Cyperus rotundus*	*Celosia argentea, Phyllanthus niruri, Cleome viscose*
Rajasthan	*Eleusine indica, Echinochloa colona*	*Cyperus rotundus*	*Commelina benghalensis, Amaranthus viridis, A. spinosus, Digera arvensis*
Tamil Nadu	*Echinochloa colona, Panicum repens, Cynodon dactylon*	*Cyperus rotundus*	*Tridax procumbens, Trianthema portulacastrum, Amaranthus viridis. Euphorbia hirta, Celosia argentea, Digera arvensis, Bergiacapensis*
Uttar Pradesh	*Cynodon dactylon, Echinochloa colona, Brachiaria ramosa*	*Cyperus rotundus*	*Ageratum conyzoides, Commelina benghalensis, Phyllanthus niruri, Trianthema portulacastrum*
Uttarakhand	*Paspalum dilatatum, Digitaria ciliaris, Setaria glauca*	*Cyperusdefformis, C. iria*	*Galinsoga parviflora, Persicaria capitatum, Oxalis latifolia*
West Bengal	*Cynodon dactylon, Digitaria sanguinalis*	*Cyperus rotundus*	*Croton bonplandianum, Commelina benghalensis, Celosia argentea*

Table 2: Critical crop-weed competition period in millets.

Crop	Critical crop-weed competition period (days after sowing)	References
Sorghum	28–42	[15]
Pearl millet	15–30	[16]
Finger millet	25–42	[17]
Kodo millet	30–35	[10]
Foxtail millet	20–35	[18]

Table 3: Yield loss due to weed infestation in millets.

Crops	Reduction in grain yield (%)	References
Sorghum	15–83	[19,20]
Pearl millet	35–90	[21]
	31–46	[22]
	16–94	[23]
	40	[24]
	46	[25]
	55	[26]
Finger millet	55–61	[27]
	5–70	[28]
	73	[29]
Barnyard millet	30	[30]
	50	[31]
Kodo millet	35–51	[32]
	55	[33]
	55–61	[10]
	68	[34]

4. WEED MANAGEMENT METHODS

We know that weeds are undesirable and those cannot be completely eradicated from agricultural fields. Rather their population should be managed and kept under control under the economic threshold limit. The critical crop-weed competition period is the most critical time for the competition which is between the crop and weeds for the common growth resources. Millets face high crop-weed competition during the early growth stage, that is, initial 46 weeks, which is important for weed management as the crop growth in that period is slow. Once the crop attains a height of approximately 0.5 m, it keeps the pace to compete with the weeds and shows dominance over weeds. Therefore, appropriate methods, namely, preventive method, mechanical method, cultural method, and chemical method should be adopted to reduce the weed thrust in the early stage of millets. An integrated approach to weed management, that is, integrated weed management (IWM) always proves to be better than other sole approaches. The weed management strategies are given below.

4.1. Preventive Method

We all are acquainted with the proverb often used in weed control "One-year seeding, seven years weeding." Nature has equipped the weeds with immense potential to be well disseminated through various means and thrive well in various drastic and unfavorable environmental conditions. As we know that "Prevention is better than cure," so it is better to prevent the weed species to spread in the croplands and infest the crop. No weed control strategy is successful if timely and adequate preventive measures are taken. Therefore, keeping in view the economic and practical feasibility, the probable means of weed seed dispersal and distribution throughout the field should be avoided to check the menace caused by the weeds in millets. The strategies are as follows:

i. Use of weed-seed-free seeds of millets
ii. Use of clean agricultural implements
iii. Use of weed-seed-free irrigation water
iv. The irrigation channel should be free of weed plants
v. Use of well-decomposed compost or farm yard manure
vi. Maintenance of farm hygiene that prevents the every year production of seeds, tubers, and rhizomes of already present weed species on the farm.

4.2. Mechanical Method

The mechanical method of weed control is the physical method of weed removal from the field which is often adopted in millets. This is one of the effective methods of weed control that ensure complete control of weeds during the desired period of crop growth. Weeds are abundant seed producers. The seeds fall on the ground and remain dormant for days to years and germinate when favorable environment appears. Several weeds propagate through vegetative propagules such as swollen roots, rhizome, and bulbs which remain inside the soil and help the weeds to survive year after year in the field. The mechanical method of weed control helps in weed seed burial as well as the removal of weed plant and vegetative propagules from the soil of the cultivated field which reduces the weed thrust in the field eventually reducing the crop-weed competition and enhancing the crop yield. The mechanical method includes manual hand weeding, deep summer tillage, fallow-season tillage, pre-plant tillage, and post-plant shallow tillage/intercultivation. Millets are mainly grown in semiarid areas where intercultivation helps in the conservation of soil moisture. Vijaymahantesh *et al*. [35] reported satisfactory weed control in conventional tillage which might be attributed to the stimulatory effect of tillage in inducing the germination of weed seeds which might be due to more deposition of weed seeds on the soil surface which might be killed by repetitive cultivation that consequently reduced the weed population increasing the yield of finger yield. In an investigation of finger millet, Sidar and Thankur [36] found that summer tillage recorded lower weed population and dry matter leading to higher grain, stover yield, and harvest index. In an experiment on pearl millet in the West African Sahelian zone, seasonal weed growth was reduced and crop yield was increased by pre-sowing tillage [37]. However, in the rainy season or *kharif* season most of the time, the clouds persist in the sky and rain occurs which delay the intercultural operations, by the time weeds grow faster and overtake the crop subsequently causing a severe reduction in millet yield. Moreover, the rise in labor cost and non-availability of an adequate number of laborers during the peak period of requirement is serious problems that do not enable the farmers to do timely manual weeding intensively in larger areas of millet production.

4.3. Cultural Method

Cultural methods of weed control are the environment-friendly methods that are adopted during crop husbandry in a standing crop through different cultural management such as plant population management through seed rate, crop spacing management, intercropping, crop rotation, mulching, management of time, and method irrigation and nutrient application. Growing intercrops such as green gram, cowpea, soybean, and ground nut could suppress the weed population by their high growth rate during the early period of crop growth, which eventually smothers the weeds so that the weed plants do not get adequate sunlight. In the same way, the increase of plant population by increasing seed rate or by narrow spacing, early application of nitrogen, and its placement at the root zone increase the plant vigor which enables the plant to utilize adequate growth resources having higher competitive ability than the weeds [30]. revealed that a higher seed rate, that is, 15 kg/ha registered lower weed dry weight and higher grain yield, B:C ratio, and weed control efficiency than the recommended seed rate, that is, 10 kg/ha at 25 cm row to row spacing in barnyard millet in a 3-year experiment at Ranichauri, Uttarakhand. Similarly, [31] reported that in barnyard millet, 25 cm × 10 cm spacing recorded higher seed yield with higher weed control efficiency than 30 cm × 10 cm and 40 cm × 10 cm spacing. Weed competition was reported to be reduced by narrow row spacing (<30 cm) which increased the yield of foxtail and proso millets [38,39]. Different conservation practices such as the opening of conservation furrow and intercropping of red gram with finger millet increased the yield of finger millet reducing the weed population and dry weight [36]. Intercropping of pearl millet and green gram at a pair row ratio of 2:2 was found to be superior to the sole crop of pearl millet being the most profitable getting a higher net return and land equivalent ratio [40]. Stale seedbed technique followed by two intercultivation at 20 and 35 days after planting showed higher crop growth parameters such as dry matter accumulation, leaf area index, plant height, crop growth rate, and lower weed density and dry weight which consequently resulted in higher grain yield, that is, 5365 kg/ha [41]. Mulching at 21 days after sowing also exhibited increased control over weed infestation and increased the yield of pearl millet [42].

4.4. Chemical Method

The chemical method is the most popular and easiest method of weed control as it saves cost, time, labor, and controls the weeds effectively and efficiently. Herbicidal control of weeds is considered to be the most important tool in weed management as it provides effective control over weeds accelerating the crop growth from the beginning thereby providing a competitive advantage to the crop over the later emergent weeds. Herbicides are divided into three categories based on when they are applied: pre-planting herbicides (applied before crops are planted; an example of this is fluchloralin), pre-emergence herbicides (applied after crops are planted but before weeds emerge; an example of this is atrazine, pretilachlor, metolachlor, and pendimethalin), and post-emergence herbicides (Applied after the emergence of weeds, e.g., 2,4-D, bispyribac-sodium). In conservation agriculture, chemical weed control has become a crucial component of weed management [43]. Herbicide combinations are advised for broad-spectrum weed control in millets since individual herbicides only have narrow-spectrum weed-controlling abilities. According to Ramakrishna *et al*. [44], pre-emergence applications of metolachlor at 1.0–1.25 kg/ha, combinations of atrazine and metolachlor, or sequential applications of metolachlor and bentazon, atrazine at 0.75 kg/ha all produced results that were comparable to repeated weedings in grain sorghum. According to Kalyansundaram and Kuppuswamy [45], the best weed control and grain production were achieved by applying a tank mix of butachlor and atrazine at 0.75 kg/ha and 1 HW at 45 DAS. According to Wu *et al*. [46], planting sorghum with atrazine and metolachlor mixed into the soil resulted in effective seasonal control of barnyard grass (*E. colona*). Pretilachlor + dimethametryne at 2.5 kg/ha, cinosulfuron at 0.05 kg/ha, or piperophos + cinosulfuron at 1.5 kg/ha all yielded greater grain yields of sorghum, according to Ishaya *et al*. [47]. They also successfully suppressed weeds, enhanced crop vigor and plant height, and decreased plant damage. Similarly, sequential applications of herbicides are recommended for season-long weed control in millets. In finger millet, isoproturon at 0.5 kg/ha (pre-emergence) *fb* 2,4-D (Na salt) at 0.5 kg/ha (post-emergence) [48] and oxadiargyl at 0.08 kg/ha (Pre-emergence) at 3 DAS *fb* ethoxysulfuron at 0.012 kg/ha (post-emergence) at 30 DAS [8] were reported to have broad-spectrum weed control. Saini *et al*. [49] observed that atrazine at 1.5 kg/ha (pre-emergence) *fb* 2,4-D at 1 kg/ha (post-emergence) at 40 DAS effectively control a wide range of weed flora in sorghum. Application of pendimethalin at 0.75 kg/ha (Pre-emergence) *fb* 2,4-D (Na Salt or Dimethyl amine) at 0.5 kg/ha (post-emergence) at 25–30 DAS provided more consistent weed control than application of post-emergence herbicides only in pearl millet [50]. Many herbicides have been standardized and evaluated for effective weed control in sorghum, but the literature is limited for other minor millets. However, the recommended herbicides for effective weed control in different millets are shown in Table 4.

4.5. Integrated Weed Management in Millets

Herbicidal weed control is more successful and efficient than traditional weed control methods; however, chemical weed management also takes into account crop stage, application time, weed variety, and weed emergence patterns. Herbicide resistance in weeds develops over time as a result of repeated usage, making weed management challenging. To reduce weeds, integrated weed management (IWM), which combines a number of separate management tactics, has been created. Instead of relying just on one method, IWM takes a holistic approach that integrates mechanical, cultural, and chemical methodologies. IWM is more environmentally and financially sustainable. The literature has reported on a number of IWM strategies, which are included in Table 5.

5. MANAGEMENT OF *STRIGA* – A CASE STUDY

Striga, a partial root parasite, is one of the most destructive weeds in millets in subsistence agriculture, reducing the output. On its ability to develop and survive, it depends on a complicated host-parasite connection. The commencement of the haustorium, which is how *Striga* attaches to the host roots, and the early chemical signals required for seed germination are released by host roots. It seems that subsequent developmental impulses are conveyed directly, through vascular tissue, when Striga invades the host root. More recent information indicates that *Striga* species are believed to cause 50 million hectares of damage and 300 million farmer losses in Africa, totaling $US 7 billion [84]. *Striga* alone reduced the grain yield of the sorghum crop in India by 75%. [85,86]. In sub-Saharan Africa, *Striga hermonthica* caused crop losses of between 70 and 100% for sorghum and pearl millet [87]. Manual hand weeding, the most common management technique used by small-scale and marginal farmers, is only operative when there are few *Striga* species present. However, as hand-pulling is ineffective against a dense population of the weed, new or light infestations should be prevented from getting worse and as part of integrated techniques for management of moderate infestations. Plants that are removed within 2 to 3 weeks after the start of blooming should be taken out of the field and burned to stop seeds from being produced and shed from the drying plants. Domestic herbivorous animals should not be fed with *Striga* plants since it may be subjected to endozoochorous dispersal of the weed seeds.

Table 4: Recommended herbicides, herbicide mixtures, and sequential application of herbicides for weed control in millets.

Millets	Herbicides	Dose (kg/ha)	Time of application	Weeds controlled	Remark	References
Sorghum	Atrazine	0.75–1.0	Pre-emergence/early post-emergence	Effective against a wide range of weeds (Broad spectrum) but some grasses are tolerant	For sole crop only. Did not control *Acrachne racemosa, Brachiaria reptans* and *Commelina benghalensis*	[51]
	Pendimethalin	0.75–1.0	Pre-emergence	Effectively controls the grasses	Suitable for intercropping, higher doses may cause phytotoxicity	[52]
	Alachlor	1.5–2.0	Pre-emergence	Effectively controls the grasses	Suitable for intercropping	[52]
	Metolachlor	1.0–1.5	Pre-emergence	Effectively controls the grasses	Suitable for intercropping	[52]
	2,4-D	0.50–0.75	Post-emergence (4–6 WAP)	Effectively controls the BLWs	For sole crop only. Good as sequential application to pre-emergence herbicides	[52]
	Atrazine+ pendimethalin	0.75+0.75	Pre-emergence	Effective against a wide range of weeds (Broad spectrum)	For sole crop only	[52]
	Atrazine+ alachlor	0.75+0.75	Pre-emergence	Effective against a wide range of weeds (Broad spectrum)	For sole crop only	[52]
	Atrazine+ metolachlor	0.75+0.50	Pre-emergence	Effective against a wide range of weeds (Broad spectrum)	For sole crop only	[52]
	Atrazine *fb* 2,4-D	1.5 1.0	Pre-emergence At 40 DAS	Effective against a wide range of weeds (Broad spectrum)	For sole crop only	[49]
Pearlmillet	2,4-D (Ethyl ester)	0.50–0.75	Post-emergence (At 4–6 WAS)	Effectively controls the BLWs	For sole crop only. Good as sequential application to pre-emergence herbicides	[53]
	Atrazine	0.50	Pre-emergence/early post-emergence	Effective against a wide range of weeds (Broad spectrum) but some grasses are tolerant	For sole crop only	[54]
	Oxadiazon	1.0	Pre-emergence	Effectively controls the annual grasses and BLWs	For sole crop only	[55]
	Pendimethalin	0.75–1.00	Pre-emergence	Effectively controls the grasses	Suitable for intercropping	[55]
	Saflufenacil	0.05	Pre-emergence	Effective against a wide range of weeds (Broad spectrum)	For sole crop only	[56]
	Pendimethalin *fb* 2,4-D (Na Salt or Dimethyl amine)	0.75 0.5	Pre-emergence Post-emergence	Effective against a wide range of weeds (Broad spectrum)	For sole crop only	[50]
Finger millet	Oxadiargyl *fb* Ethoxysulfuron	0.08 0.012	3 DAS 30 DAS	Effective against a wide range of weeds (Broad spectrum)	For sole crop only	[8]
	Butachlor	0.75	Pre-emergence	Effectively controls the grasses	For sole crop only	[57]
	Isoproturon *fb* 2,4-D Na salt	0.5 0.5	Pre-emergence Post-emergence	Effective against a wide range of weeds (Broad spectrum)	For sole crop only	[48]
	Bensulfuron-methyl+ pretilachlor	0.06+0.60	Pre-emergence (2 DAT)	Effective against a wide range of weeds (Broad spectrum)	For sole crop only	[59]
Kodomillet	Bensulfuron-methyl+ pretilachlor	0.33	Pre-emergence/early post-emergence	Effective against a wide range of weeds (Broad spectrum)	For sole crop only	[10]
	Bispyribac-sodium	0.02	Post-emergence (20 DAT)	Effectively controls the grasses	For sole crop only	[9,60]
Prosomillet	Atrazine	0.28–0.56	Pre-emergence	Effective against a wide range of weeds (Broad spectrum)	For sole crop only	[61]

(*Contd...*)

Table 4: (*Continued*).

Millets	Herbicides	Dose (kg/ha)	Time of application	Weeds controlled	Remark	References
	Propazine	0.28–0.56	Pre-emergence	Effective against a wide range of weeds (Broad spectrum)	For sole crop only	[61]
	2,4-D	0.56	Post-emergence (4–6 leaf stage)	Effectively controls the BLWs	For sole crop only	[62]
	Carfentrazone+2, 4-D amine+ dicamba	0.009+ 0.280+0.140	Post-emergence (2–5 leaf stage)	Effective against a wide range of weeds (Broad spectrum)	For sole crop only Good control on *Kali tragus*, *Lactucaserriola* and *Helianthus annuus*	[63]
Foxtail millet	Carfentrazone + 2,4-D amine+ dicamba	0.009+ 0.280+0.140	Post-emergence (2–5 leaf stage)	Effective against a wide range of weeds (Broad spectrum)	For sole crop only Good control on *Kali tragus, Lactucaserriola* and *Helianthus annuus*	[63]
	Carfentrazone	0.018	Post-emergence	Effectively controls the sedges and BLWs	For sole crop only	[63]
	Tribenuron-Methyl	22.5	Post-emergence	Effectively controls the BLWs	For sole crop only	[64]
Little millet	2, 4-D sodium salt	1.00	Post-emergence (20–25 DAS)	Effectively controls the BLWs	For sole crop only	[65]
	Isoproturon	1.00	Pre-emergence	Effectively controls the grasses and BLWs	For sole crop only	[65]

*DAS: Days after sowing; DAT: Days after transplanting; WAP: Weeks after planting

Cultural methods, namely, removing the residues in sorghum fields after harvest, adoption of crop rotation of host crops with non-host and catch crops, mixed croping without host crops, application of high dose of nitrogenous fertilizer as top dressing, and growing resistant or tolerant cultivars help reduce the witch weed infestation. Whatsoever strategy is used, the ultimate objective must be to stop all *Striga* seed production while retaining control if necessary throughout and after harvest. Trap crops are not themselves harmed, but *Striga's* growth is encouraged. *Striga* seeds that are not fed by the plant root never develop. It is therefore possible to cycle these crops with sorghum to promote suicidal germination. It might be difficult to find an appropriate selective herbicide to manage *Striga* in field crops. Pre-plant/pre-emergence herbicides such as atrazine and oxyfluorfen have some, but ineffectual, effect on *Striga* due to its broad leaves. Spraying 2,4-D on the leaves of *Striga* after emergence is effective. However, sorghum is vulnerable to stalk twisting and lodging if 2,4-D is sprayed within the leaf whorl; therefore, adequate precautions should be taken during spraying. An experiment on maize and sorghum revealed that seed treatment with 2,4-D effectively controlled *Striga* infestation [88]. Development of transgenic herbicide resistant sorghum cultivar can be an alternative approach of controlling the witch weed [89]. Biological control using the natural enemies of *striga* is also an promising approach which can effectively control *Striga* infestation. Ciotola *et al.* [90] reported that the *Fusarium oxysporum* f.sp. *strigae* isolate controlled *Striga* effectively up to 90%, where the fungus parasitizes in the rhizosphere of the sorghum plants inhibiting the germination, emergence and development of *Striga* before it penetrates the sorghum roots [91]. There is need to develop integrated *Striga* management programs which are cheap that can be easily adoptable by the small and marginal farmers.

6. FUTURE NEEDS

Millets are regarded as "Nutri-cereals" as they have high nutritional qualities. They are being claimed as future food considering the harsh conditions going to be due to climate change. Hence, in the future, the demand for millets will be high warranting higher production. These crops are mainly grown in the rainy season on marginal lands by resource-poor farmers where the crops do not get improved production management. Hence, weed management aspect is given less importance in this scenario. Mostly, the improved weed species of cereals are cultivated as minor millets. Therefore, in the early stage of crop growth, it is very difficult to differentiate between crops and weeds. The farmers become able to do hand weeding when the weeds have already gotten older and accumulated greater amount of dry matter. Up to this stage, weeds deprive the crop from different growth resources such as soil moisture and nutrients out of the severe crop-weed competition which drastically reduces the yield. Therefore, the weeds should be identified in the early stage of the crop and removed from the crop field. For this purpose, low-energy input manual or mechanical weeders should be developed. No doubt herbicides control weeds effectively and efficiently in millets. Among millet crops, herbicides are mostly used in finger millet and pearl millet. It is seen that chemical weed control is not often used in other minor millets. However, most farmers are unaware of the proper use of herbicides and they have the thought that the herbicides will reduce the quality of grain and fodder of millets. Hence, they need to be educated regarding the proper time and method of herbicide usage. Moreover, fewer herbicide options are available in the literature for minor millets. Hence, there is a need for more research on the standardization and evaluation of herbicides in different minor millets. More emphasis should be given to IWM practices that will be economically and ecologically sustainable for different agro-climatic zones considering the changing climatic scenario.

Table 5: Integrated weed management in millets.

Crop	Integrated weed management strategies	References
Sorghum	Metolachlor at 1.0 kg/ha or atrazine at 0.75 kg/ha (PE) followed by one manual weeding at 30 DAS	[44]
	Atrazine at 0.5 kg/ha (PE) *fb*2,4-D at 0.75 kg/ha (POE) at 20 DAS *fb* inter-culturing at 30 DAS	[66]
	Atrazine@ 0.50 kg/ha (PE) *fb* atrazine @ 0.50 kg/ha (POE) at 25 DAS *fb* HW and intercultivation at 40 DAS	[67]
	Atrazine 1.5 kg/ha (PE) *fb* 1 HW at 50 DAS	[68]
	Combination of smothering effect, allelopathy and delay in sowing time (Intercropping with soybean+seed treatment with *Parkia biglobosa* pulp+seed sowing in July to get high relative humidity due to established rainfall in July in Nigeria) showed good control over *Striga hermonthica.*	[69]
	False seed bed+Sorghum-Wheat cropping system reduced the weed thrust in the cropping system	[70]
Pearl millet	Atrazine at 0.5 kg/ha (PE/early POE) at 10 DAS *fb* 1 HW at 30 DAS	[71]
	Pendimethalin at 1.50 kg/ha *fb* 1 HW 40 DAS	[72]
	Pendimethalin at 1.0 kg/ha (PE) or Oxadiazon at 1.0 kg/ha (PE) *fb* 1 HW at 45 DAS achieved broad spectrum weed control	[55]
	Fluchloralin at 1.0 kg/ha *fb* 1 HW at 40 DAS	[73]
	Pendimethalin 0.75 kg/ha (PE) *fb* 1 HW at 6 WAS	[74]
	Atrazine 0.75 kg/ha (PE) *fb*1 HW at 30 DAS	[75]
Finger millet	Metoxuron at 0.75 kg/ha (PE) *fb* 1 HW at 30 DAS	[76]
	Isoproturon at 0.5 kg/ha (PE) *fb* 2 hand intercultivation at 20 and 40 DAS	[77]
	Oxyflurofen at 0.50 kg/ha *fb* 2 HW at 20 and 45 DAS	[78]
	Bensulfuron methyl+Pretilachlor at 3 kg/ha (pre-mix formulation) *fb* one inter-culture at 45 DAS	[79]
	Oxadiargyl 80 WP at 0.15 or 0.20 kg/ha (within 3 DAS) *fb* one intercultivation at 25–30 DAS	[80]
	Bensulfuron ethyl 0.6+Pretilachlor 6.0 G at 0.33 kg/ha (within 3 DAS) *fb* one intercultivation at 25–30 DAS	[80]
	Bispyribac sodium 10 SC 0.01 or 0.015 kg/ha (within 15–20 DAS) *fb* one intercultivation at 35–40 DAS	[80]
Kodo millet	Butachlor 50 EC at 0.75 kg/ha (within 3 DAS) *fb* one inter cultivation at 25–30 DAS	[80]
	Bensulfuron ethyl 0.6 G+Pretilachlor 6.0 G at 0.165 kg/ha *fb* one inter cultivation at 25–30 DAS	[80]
	Bispyribac-sodium 10 SC 0.015 or 0.010 kg/ha (15–20 DAS) *fb* one intercultivation at 35–40 DAS	[80]
	Isoproturon at 0.5 kg/ha *fb* two intercultivations	[81]
	Isoproturon at 0.75 kg/ha *fb* HW at 40 DAS	[34]
	Isoproturon at 0.5 kg/ha *fb* 1 intercultivation at 20 DAS *fb* 1 HW at 40 DAS	[32]

(*Contd...*)

Table 5: (*Continued*).

Crop	Integrated weed management strategies	References
Barnyard millet	Isoproturon at 0.5 kg/ha *fb* one inter-culture at 40 DAS	[30]
	Spacing of 25 cm×10 cm+2 HW at 20 and 40 DAS	[31]
	Bensulfuron methy l 0.6 G+Pretilachlor 6 G at 0.495 kg/ha (PE) at 3 DAS *fb* 1 HW at 20 DAS	[82]
Foxtail millet	Pretilachlor 0.5 kg/ha (PE) at 1 DAS *fb* 1 intercultivation at 20 DAS OR Pyrazosulfuron-ethyl 0.015 kg/ha (PE) at 1 DAS *fb* 1 intercultivation at 20 DAS	[83]

*PE: Pre-emergence; POE: Post-emergence; HW: Hand weeding; DAS: Days after sowing; *fb*: followed by

7. CONCLUSION

Weeds compromise the yield of millets like other crops. In the future, millets are going to have high demand in the market. Weeds are difficult to be identified in the early stage of crop growth and in that period, weeds cause drastic loss of costly external inputs like water and fertilizer depriving the crop of millets of that. To reduce crop loss due to weed infestation in millets, timely and proper weed management strategies, namely, preventive methods, mechanical methods, cultural methods, and chemical methods should be adopted in an integrated manner according to the prevailing situation of weed diversity, climatic conditions, and crop ecology. Across the current era of precision agriculture, precise weed management may also be used to intense weed control in bigger regions employing robots, drone technology, and machine learning, which will not only minimize the environmental impact of herbicide use but also sustainably boost profitability to the large millet growers.

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All the sources of data provided in this manuscript have duly been referred in the references which are freely available in public domain.

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