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REVIEW ARTICLE

Weed management under climate change in future grain millets

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ABSTRACT

Climate change is a natural phenomenon in earth's environmental system and used to happen over hundreds or thousands of years, but now it is happening within few decades due to increasing human population and associated activities which are responsible for production of more CO_2, methane, N_2O and small quantities of HFC's. This is expected to increase because the projected global population is 11.2 billion by the end of 21st century from the present 8.1 billion as on 2024. Under climate change, increased CO_2 is seen as an advantage for C_3 food crops but concomitant increase in temperature negated this impact favouring C_4 crop production, hence, most weeds which are C_4 in nature are threat to agriculture production. Unlike C_3 cereal crops which are the staple foods, millets being C_4 have advantage to compete with C_4 weeds and millets are more nutritious and drought tolerant. It is a real challenge to plant scientists to sustain and increase the food production. Hence, in this review an attempt is made to critically evaluate existing literature and provide insights to the researchers and policy makers to promote the millets to meet the food and nutritional security for the ever growing population.

Keywords: Climate change, Millets, Weeds, Weed management, Herbicides

INTRODUCTION

The energy required for all the living beings on earth is provided by an important physiological process called photosynthesis in Plants (autotrophs). During photosynthesis light energy is trapped and used to convert water, CO_2 and minerals into oxygen and energy rich compounds. These energy rich compounds are the source of energy for heterotrophs (humans, animals and all other living creatures).

In the whole process CO_2 is one of the important inputs present in the atmosphere. CO_2 is constantly being exchanged among the atmosphere, Ocean and land surface as it is being both produced and absorbed by many microorganisms, plants and animals. However, emission and removal of CO_2 by these processes tend to balance. But, the industrial revolution began in 1970 changed the balance of CO_2, since human activities have contributed substantially to climate change by adding CO_2 and other heat trapping gases (GHG) like methane and nitrous oxide.

The main human activity that emits CO_2 is the combustion of fossil fuels (coal, natural gas and oil) for energy and transportation to meet the needs of the growing population. In addition, certain industrial processes and land use changes also emit CO_2. Of the 3 important GHG's (CO_2, CH_4 and N_2O), CO_2 concentration substantially increased after the industrial revolution and concomitant increase in global population. According to the EPA, CO_2 accounts for 82% of all GHGs from human activities. The GHGs that impact the gradual warming of the earth's surface are those that stay in the atmosphere for a long period (like CO_2) and build up over time and the warming power of the gas and the length of time it stays in the atmosphere **(Table 1)**.

The atmospheric concentration of CO_2 is 0.04%, CH_4 is 0.002% and N_2O-0.00003%. Although the warming potential of other gases is more powerful than CO_2, its emissions dwarf those of other gases due to its large volume of emissions. Human activities have raised atmospheric CO_2 by 50%, meaning the amount of CO_2 is now 150% of its

Table 1. Global warming potentials and atmospheric lifetimes (years)

Green House Gases	Atmospheric Lifetime	Global warming potential over 100-year lifetime
Carbon Dioxide (CO_2)	50-200	1
Methane (CH_4)	12	21
Nitrous Oxide (N_2O)	114	289
Other	1-50,000	5-22,800

Source: Intergovernmental Panel on Climate Change, 2007 Report

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value compared to the pre-industrial era. This is greater than the natural CO_2 source. It has risen from 280ppm in late 1700's to 419ppm in 2023 and 422ppm in august, 2024. Increase in the amount of GHGs in the atmosphere attributed mainly to human activity, which caused an unbalance in the process called greenhouse effect. Hence, slowly the availability of the earth's atmosphere to absorb heat from the subsurface has increased and with it the temperature of the atmosphere. This is known as "Global warming".

Millets are a small grain which are predominantly grown and consumed after cereals in the world especially in Africa and Asia (Mishra 2015). There are an estimated 1.2 billion people who consume millet as a part of their diet [WFP]. Millet is a staple and it is a very good substitute for oats and cereals. Millets are rich in minerals and vitamins and pearl millet is a rich source of proteins. Another millet finger millet, is the only food grain which has 320 to 344 milligram Ca^{2+} for 100 gram of grain. Millets have a higher nutritional profile that ensures better health benefits (NAAS 2013). India is the World's largest producer of millet following China and Nigeria, and supplies 41% of global output (Kumar *et al.* 2019). The millets commonly grown in India include Sorghum, pearl millet, finger millet, barnyard millet, proso or common millet, foxtail/ Italian millet, kodo millet, little millet etc. The area, production and yield of millets in India is presented in **Table 2**.

The area under cultivation of millet declined due to a change in conversion of irrigated area for wheat and rice cultivation. Hence, unavailability of millets, low yield, change in consumption pattern under dietary habits resulted in fall in the levels of vit-A, protein and iron that lead to malnutrition. Millets occupy a relatively lower position in Indian agriculture, though they are important from the point of food and nutrition security, especially quality of food.

Millets are best options under hot and dry conditions compared to the cereals and predominantly grown in rainfed conditions. The key issue is controlling weeds, since during the rainy season there will be increased soil moisture and relatively high temperature that will favour the weed growth. The competition for resources (sunlight, water and nutrients) between crop and weed can result in lower yield and lower quality crops (Mishra *et al*. 2018). Higher growth of weeds may impede harvesting, increasing its difficulty and duration (Mahalingam *et al*. 2019).

Table 2. Area, production and productivity of millets in India (2022-23)

Crop	Area (m ha)	Production (mt)	Productivity (kg/ha)
Pearl millet	7.57	11.43	1510
Sorghum	3.54	3.81	1079
Finger millet	1.16	1.69	1454
Other minor millets	0.43	0.38	898
Total	12.70	17.32	-

(Source**:** https://www.indiastat.com/table/agriculture/season-wise-area-production-yield-nutri-cereals-in/1210178)

The management of weeds is very crucial to prevent the resource acquisition by weeds which are otherwise meant for crops. The yield loss due to weed can range from 15 to 97% (Dubey *et al.* 2023) in millets due to increased temperature and change in precipitation pattern (Vikarm *et al.* 2021 and Xiaoyan *et al.* 2018). In addition to this climate change can affect the efficacy of herbicides, by breakdown and effectiveness of herbicides. This needs change in use of alternative herbicides. So far, the findings suggest that, holistic approach is required to effectively control weeds to sustain the millet productivity.

Millets are termed as the "miracle grains" or "crops of the future", as they are not only grown under harsh conditions but are drought-resistant crops with fewer inputs. They are dual-purpose crops as they provide both food and fodder providing food security and economic efficiency of farming. Millets will contribute to mitigating climate change by reducing CO_2 in the atmosphere, whereas wheat being a thermally sensitive crop and paddy is a major contributor of climate change through Methane emission. Normally do not depend on use of chemical fertilizer and attract less pests and have a high nutritive value. Millets are superior to rice in terms of nutritional benefits. They are rich in fiber, protein, Vitamins and minerals and have a higher antioxidant content than rice. In fact, foxtail millet and kodo millet are suggested as substitutes for rice. And finger millet is a great substitute for Rice and Wheat for diabetes. And also millets help in curling obesity, lowers the risk of hypertension, cancers, helps in preventing constipation and have low glycemic index. Realizing the importance of millets **(Figure 1)** both from the point of food and nutrition security, Indian government has initiated a program "Initiative for nutritional security through intensive millet promotion-INSIMP a part of Rastriya Krishi Vikas Yojana-RKVY. And Indian government proposal to FAO in 2018, finally accepted by the United Nations General assembly and declared 2023 the "International year of millets".

Weeds under millets cropping systems

Climate change is one of the most important aspects that can cause alterations in weed

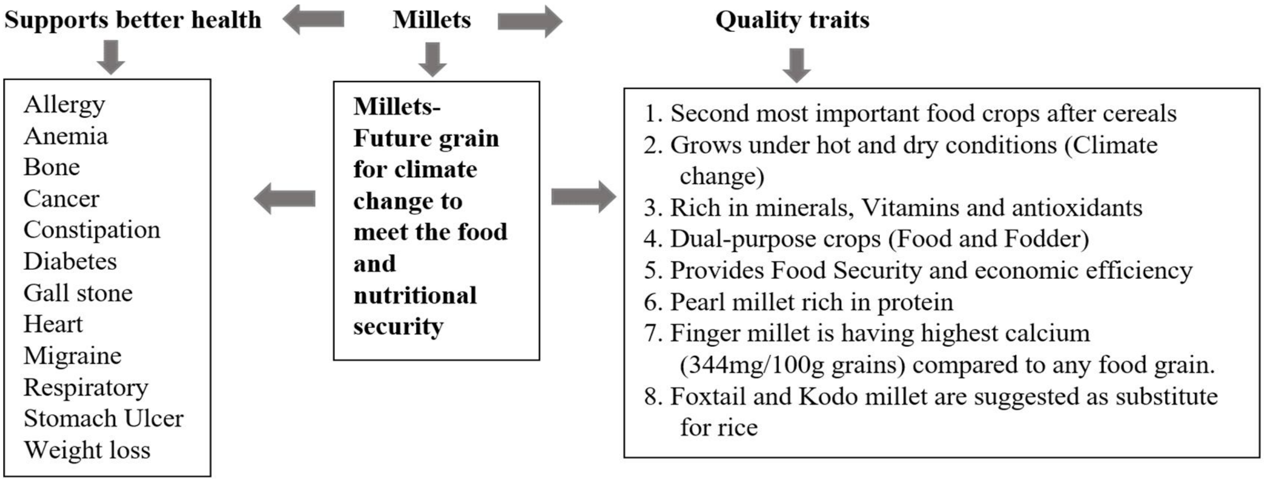

Figure 1. Quality attributes and health benefits of millets (Source: Shankar and Geetha, Unpublished data)

composition, growth, physiological development and infestation pressure. Under the circumstances many weeds may become aggressive and a few weed species may become inactive so that weeds with less phenotypic plasticity may experience population decline. The distribution of weeds depends on prevailing climate, management activities in neighboring fields, crop rotation and soil composition. Soil type is a major factor in deciding the type and variety of species growing in a particular area.

For most weeds the ideal temperature ranges from 10 to 35 °C. Initially when CO_2 levels started increasing, the scientists are of the opinion that food production will be enhanced because out of the top 15 food crops 12 are C_3 plants. C_3 plants are at an advantageous position over C_4 plants. Subsequently it was realized that there is a concomitant increase in temperature which changes the complete scenario of CO_2 fertilization impact on crop production (Jordan and Ogren, 1984, Osmond *et al.* 1982, Morgan *et al.* 2001). Weed - crop interaction has changed due to global climate change. The advantage envisaged for C_3 crops is nullified because of increase in temperature. Since, optimum temperature for photosynthesis is higher for C_4 (30-45°C) than C_3 (10-25°C) and more top millet weeds are C_4 **(Table 3)** and parthenium and striga weeds are C_3.

Weed infestation in agricultural field is one of the important biotic components hindering plant growth and productivity. They compete with cultivated crops for sunlight, water and nutrients etc. (eg: *Amaranthus Chenopodium*, Gajar Ghas *etc.)* and grow vigorously than crop plants. In addition, they harbor insects and pathogens, which attack crop plants. Weed infestation alone can reduce 50%yield in some crops. The total actual economic loss of about US$ 11billion was estimated due to weed alone in 10 major crops of India (and highest being in Rice US$ 4420 million).

Table 3. Major C4 weed species found in millets

C4 weeds	References
Cynodon dactylon	
Cyperus rotundus	Dhanapal *et al.* 2015;
Dactyloctenium aegyptium	Shubhashree &
Digitaria marginata	Sowmyalatha 2019;
Echinochloa crus-galli	Lekhana *et al.* 2021;
Euporbia hirta	Sukanya *et al.* 2021;
Elusine indica	Gurubasavaswamy *et al.*
Imperata cylindrica	2023
Monochoria vaginalis	
Elusine indica	

Climate change can also play a crucial role in weed distribution of both invasive and noxious weeds (Hakala *et al.* 2011) because it changes precipitation pattern and water availability (Rodenburg *et al.* 2011). Weeds are relatively constant and cause negative effects on agriculture, unlike other biotic stresses like insects and pathogens, which are random and irregular (Kostov and Pacanoski, 2007). Weeds can also cause extensive damage to non-agricultural land and to public health. Furthermore, weeds are known to produce harmful chemicals and serves as hosts for several insects pests and diseases (Swinton *et al.* 1994, Boydston *et al.* 2008).

Herbicides

Herbicides are commonly known as weed killers, are substances used to control undesired plants. The commonly used herbicides are alachlor, octachlor, butachlor, metachlor and propachlor. Most of them are hazardous except metachlor. There are 2 types of herbicides: selective (retard the growth of some plants) and non-selective (toxic to all plants). Herbicides are routinely applied because of their simplicity in use and greater efficacy (McErlich and Boydston. 2013). Glyphosate (N-Phosphonic methyl glycine) is a broad-spectrum herbicide that is absorbed by plant leaves and is systematic (translocated) within the plant. Glyphosate also known as the "Roundup" is the most widely used herbicide in the US. Nearly all herbaceous plants and most woody plants are susceptible to glyphosate which inhibits synthesis of 3 aa's necessary for plant growth. A large number of different classes of herbicides inhibits photosynthesis. 2, 4-Dichlorophenoxyacetic acid (2,4-D) is a common systemic herbicide used in the control of broad -leaf weeds. It is the most widely used herbicide in the world.

Crop-weed competition under climate change

Weeds tend to have higher genetic diversity and physiological plasticity than crops, allowing them to exhibit resilience and adapt better to changing CO_2 levels and higher temperature, often competing crops. Among various biotic factors, weeds cause the most substantial yield loss (34%), surpassing insect pests (18%) and diseases (Kaur *et al*. 2024). Climate change is having different effects on C_3 and C_4 photosynthetic pathways, modifying the dynamics of composition between crops and weeds. It has resulted in yield loss of 183 kg/ha in rice and 88 kg/ha in wheat (Waddington *et al*. 2010). The competition between weed and crop for limited resources such as water, light, space and nutrients leads to reduced growth, hindered development and yield losses in crops (Kaur *et al.* 2014). The positive effects of increased CO_2 on most crops are offset by high temperature, with no benefits observed for C_3 crops **(Table 4)**.

Weed management in millets

Millets are considered as "climate smart crops" since they are hardy and survive in high temperature and resistant to climate change. Weeds cause substantial crop losses particularly in less developed countries. Increase in temperature due to global climate change and high CO_2 concentration in atmosphere are likely to have a significant impact on weed biology and weed pressure which in turn will reduce crop productivity. Millets predominantly grown in rain-fed condition and nutrient deficient soils, face the risk of yield losses due to intense weed competition. So far several methods are followed to manage weeds in millets (Dubey *et al*. 2023). Agdag 1995, reported that narrow spacing (<30cm) in prosomillet found to increase the yield and within a crop varietal variation exists. Planting sorghum at higher densities (7.5 plants per meter) reduced weed density of *Echionochloa esculenta*.

Mishra *et al*. (2012) reported that the weed competitive cultivars in sorghum hybrid (CSH-16) out performed weeds by limiting the light availability. The intercropping rather than solo crop increases the usage of natural resources and superior weed control efficiency (65.8%), weed smothering efficiency (52%) and reduced weed dry weight in pearlmillet + black gram and finger millet and onion and increased yield (Vishalini *et al*. 2020). Cultivation of diverse crops season after season and leaving land fallow can suppress weeds to certain extent (Barberi and Lo Cascio 2001). Arora and Tomar (2012) reported soil solarization for 4-6 weeks is the most effective non-chemical and agronomical weed management practice for lowering weed seed bank.

Mulching inhibits penetration of sunlight to the soil slowing or preventing seed germination and growth of weed. It is more effective on small seeded annual weeds and perennial weeds such as *sorghum halpense* and *cynodon dactylon*. The striga weed (C_3 type) can be controlled by applying synthetic analogues of 'strigol' and 'strigol acetate', natural chemical stimulants suppresses weed growth. Preplant incorporation of analogues reduced 50% striga population in sorghum and ethylene treatment resulted in 90% reduction in striga seed bank (Das 2016).

Table 4. The response of C3 and C4 crops with C3 and C4 weeds under climate change scenario

Types of crops	Ambient CO_2	Climatic parameters		
		High CO_2 (> ambient CO_2)	High t°C (> ambient t°C)	High CO_2 + high temperature
C_3 crops alone	Normal	Better than C_4	No response /?	No response /?
C_4 crops alone	Better than C_3	No response	Better than C_3	Better than C_3
C_3 crop + C_3 weed	Reduced crop growth	C_3 crop better than C_3 weed	C_3 crop growth reduces	No response /?
C_3 crop + C_4 weed	Weed dominates C_3 crop	C_3 crop dominates	Weed dominates	Weed dominates
C_4 crop + C_3 weed	Better growth of C_4 crop	Weed dominates /?	Crop dominates	Crop dominates
C_4 crop + C_4 weed	No response /?	No response /?	Weed dominates	Weed dominates
C_3+ C_4 weeds in C_3 crop	No response /?	C_3 crop dominates	C_4 weed dominates	C_4 weed dominates
C_3+ C_4 weeds in C_4 crop	No response /?	C_3 crop dominates	C_4 weed dominates	C_4 weed dominates

Among the physical (mechanical) methods of weed management, tillage is known to influence the dispersion of weed seeds and propagules through the soil profile and in a rainfed pigeon pea + finger millet cropping system, a considerable reduction in weed density is reported by Vijamahantesh *et al.* 2013. Kujur *et al.* 2018, reported hoeing twice between rows significantly reduced the density and dry matter of weeds in finger millet. Hand weeding which is costlier than chemical weeding is found to be effective in suppressing annual weeds but not perennial weeds (Thanmai *et al.* 2018, Gowda and Dhanjaya 2000).

Chemical weed management

Weed control using herbicides found to be simplest way and cost effective yet environmental issues need to be taken care. However information on weed control in small millets is limited because scarcity of herbicides in millets (Vanderlip *et al.* 1998). Atrazine is found to be successful pre-emergence herbicide in millets (Ramesh *et al.* 2019) and Vinothini and Arthanari (2017) also reported Isoproturon, a pre-emergent controlled the weed density in Kodo millet. Integrated weed management of herbicides spray in combination with one hand weeding found to be effective in weed control in millets for example in Sorghum, Pearl millet and Kodo millet (Deshveer and Deshveer 2005, Girase *et al.* 2017, Lekhana *et al.* 2021 and Thambi *et al.* 2021).

Management of weeds in millets under climate change

Climate variation on weed growth

In the beginning of global warming, scientists were very enthusiastic feeling that the higher levels of CO_2 in the atmosphere (termed as CO_2 fertilization) can act as a fertilizer and increase plant growth because most of the crop plants are C_3. Similarly, they thought there will be an advantage for C_3 crops to compete better with weeds, since most of the weeds are C_4. The studies conducted to manage weeds in millet fields are summarized as below. Pre-emergence application of Atrazine at 0.5 kg/ha + one hand weeding at 35 days after sowing and the post-emergence application of atrazine 0.4 kg/ha +one hand weeding at 35 days of sowing gave best control in pearl millet (Girase *et al.* 2017). In case of Kodo millet, research revealed that post-emergence herbicide application of bispyribac sodium 20 g/ha on 20 days after transplant had controlled weeds of all kinds in transplanted kodo millet Jawahar *et al.* (2020).

In *Kharif* (2018), in a transplanted finger millet, an experiment was conducted to evaluate the weed control in the field. The results showed that the pre-emergence application of biosulfuran-methyl 0.6G at 60 g/ha + pertilachlor 6G at 600 g/ha followed by early post-emergent application of bispyribac-sodium 10SC at 25 g/ha had the lower total weed density, total weed dry weight and greater Weed Control Efficiency. Ramadevi *et al.* (2021), reported greater grain production was obtained by applying 20 g/ha of phenoxsulam post-emergence (PoE) in transplanted finger millet. Applying isoprotaron 750 kg/ha prior to emergence and manual weeding 40 days post-sowing resulted in weed density & dry weight below the economic threshold (Vinothini and Arthanari 2017).

Elevated CO_2 and temperature

Climate change is the result of both increased CO_2 concentration and increased temperature. Weeds being C_4 plants have better adaptation to heat stress, due to high water use efficiency (Osmond *et al.* 1982, Long 1999, Morgan *et al.* 2001). Differential impacts of climate change variability such as temperature regimes, CO_2 and temperature levels on weeds and crops allows weeds to compete well and thrive even in unpredictable environments (Hartfield 2011). It is also reported that higher temperature enhances mineralization processes that increase the nutrient availability to plants (Beier 2004, Schmidt *et al.* 2002). Prolonged drought leads to dehydration of roots and reduced soil nutrient mobility impede root activity and nutrients uptake (Hinsinger *et al.* 2009). Dynamics of nutrients between crop and weeds is also influenced by elevated CO_2 (Zeng *et al.* 2011).

Weeds are managed by several ways. Of these, herbicides application for weed management is cost-effective and more reliable method. But, under climate-change scenario, elevated levels of CO_2 high temperature, precipitation, Relative humidity and solar radiation are the factors that alter the herbicide efficacy. High CO_2 and high temperature have contrast effect on herbicide entry through the leaf and translocation to the weed plants. Under high CO_2 more biomass produced by weeds may cause dilution effect and lower the efficacy of herbicide. Similarly roots grow deeper into soil layers preventing the uptake of herbicides which are present in the surface and top layer of soil (Manea *et al.* 2011). Whereas, under high temperature enhances the root uptake of herbicides due to a decrease in soil organic matter and high evaporation rates (Miraglia *et al.* 2009)

Reduction in stomatal conductance (around 50% in some plants) and leaf thickening which causes stomatal closing and increase in leaf starch concentration due to elevated CO_2 in weeds helps them to survive from post-emergence herbicides (Ziska 2008, Jackson *et al*. 2011). On the other hand, high temperatures are known to alter and lower the viscosity of cuticular lipids which in turn influences the permeability and diffusion of herbicides through the cuticles. Other temperature dependent processes such as phloem translocation, respiration and protoplasm streaming in plants will affect the efficiency of herbicides under high temperature. Not only above ground temperature, even high soil temperature causes decrease in permeability, increasing volatility and microbial breakdown affecting the efficacy of herbicides. For example at high soil temperature (25^{o}C), triallate volatilization increased from 14 to 60% in sandy and 41 % in loamy soils (Atienza *et al*. 2001). These studies suggest that increased dose or number of applications of herbicides may become the order of the day in the future under climate change scenarios.

Precipitation and relative humidity

Global climate change influences precipitation patterns and Relative humidity. These two parameters accompanied by warmer temperature leads to extreme drought and as well flooding (Clements *et al*. 2014). Intense rainfall immediately after herbicide application may dilute the concentration by washing off spray droplets and reduce herbicide retention on leaf and uptake. On the other hand lower precipitation will enhance uptake by rewetting the dried spray droplets on the leaf surface (Olesen and Kudsk 1987) and lower the translocation and decreased transpiration within the plant lowers herbicide efficacy (Zanatta 2008, Keikothaile 2011). All pre-emergence herbicides require optimum moisture in the soil for active absorption of herbicides (Olson *et al*. 2000). Dry conditions increase the adsorption of herbicides on soil particles, which will be eventually washed off due to heavy rainfall leading to heavy loss due to leaching (Soukup *et al.* 2004).

Though optimum relative humidity is desirable at the time of spraying, at high relative humidity stomatoes remain open and helps in better uptake of herbicides into the leaf (Kudsk *et al*. 1990). Studies have shown that relative humidity could exert greater influence on the uptake of foliar sprayed herbicides than temperature (Devine *et al*. 1993, Anderson *et al.* 1993). Most of the studies suggest that high temperature accompanied with high relative humidity is beneficial for weed control by most herbicides (Stopps *et al.* 2013).

Solar radiation

Solar radiation is an important determinant, it is not only critical for plant growth and development but also important for herbicide efficacy, since it facilitates the entry of herbicide through stomata and translocation of herbicides within the plant and target sites for actions. Several herbicides such as Bentazon, Clethodim and Talkoxydim showed higher efficacy of herbicides (Hatterman-valenti *et al.* 2011). In some cases, solar radiation may directly affect the chemical properties of herbicides through photodegradation. For contact herbicides light is crucial for activation of herbicides and to increase efficacy (Wright *et al.* 1995) For example paraquat (contact herbicide) efficiency decreased as UV radiation increased. This may be due to increased wax content as a mechanism by plants to prevent UV damage resulting in lower absorption and efficacy (Wang *et al.* 2006).

In the crop-weed competition enhancing the high interception by crop and thereby reducing the amount of the light reaching the land surface is one of the approaches, which can be manipulated by crop orientation (Borger *et al*. 2015, Holt 1995).

Millets being photo-insensitive, they can adapt to different environmental conditions, hence they are resilient to climate change. But, millets are having slow growth initially, they can't suppress weeds unless they adequately grow to shade the weeds (Mishra 2015). Hence optimising spacing between rows is very crucial, since large rows results in higher penetration of light to the soil surface favouring weed growth. Some findings suggested narrow row spacing results in higher productivity of finger millet by suppressing weeds (Fufa and Mariam 2016, Chavan *et al.* 2017).

Another cultural practice could be growing intercrops which facilitates better utilization of natural resources by crops and reducing the availability to weeds. Similar results can be obtained by increasing the seed rate, so that the crop can dominate over the weeds because of a higher population (Vishalini *et al.* 2020, Kumar *et al.*2019, Dubey *et al*. 2023, Hozayn *et al.* 2012). Any management practices that lead to faster canopy cover of the crop will substantially decrease weed germination (Locke *et al*. 2002). Vishalini *et al.* (2020) reported that intercropping of finger millet with onion increased weed control efficiency and yield and the same results found in intercropping of pearl millet and blackgram (Mathukia *et al*. 2015) and also with legume intercropping such as mungbean, cowpea, soybean and groundnut. Yet another option is mulching, which reduces light penetration to the soil surface and exerts a smothering effect on weeds (Teasdale and Mohler 2000, Kaur and Singh 2006).

Climate change is known to enhance the intensity of both flooding and drought globally (Bannayan *et al*. 2011; Challinor *et al*. 2014). To manage these situations which vary depending on the location and types of cultivation (Etana *et al*. 2022), shifting (pre or postponing) sowing date is also a type of management (Liu *et al*. 2020) strategy to prevent synchronization of crop critical growth stages (Mulla *et al*. 2019).

Weed competitive cultivars

The crop varieties selected to compete with weeds should possess competitive potential traits, which can grow faster, have canopy structure, ability to acquire and efficiently use light, moisture and nutrients better than weeds or release allelochemicals to prevent the germination of weeds (Peerzada *et al*. 2017, Buhler 2002; Stahlman and Wicks 2000; Gholami *et al*. 2013, Mishra *et al*. 2015). For example, CSH-16 sorghum hybrid known to suppress weed (Mishra *et al*. 2015). Several striga-resistant varieties/lines are developed by ICRISAT for Africa and Asia, S1561, S1477, S1511, IS 6961, IS 7777, IS 7739, IS 14825, IS 14928, Framida and P 967083. The mechanism here is to prevent attachment of striga to the plant through reducing stimulant production.

In addition to these interventions to control weeds in the future, attempts are made to develop herbicide resistant millet cultivar. In China, attempts are being made to develop novel herbicide-resistant millet varieties/hybrids by millet breeders (Darmency *et al*. 2017). But it is time consuming and laborious. The alternative would be to employ biotechnological/molecular breeding approaches to develop herbicide-resistant cultivars. Already canola, soybean varieties and corn hybrids which are resistant to herbicides are developed. At the same time, it is important to follow herbicide rotation to prevent weeds developing resistant to a particular herbicide. It may not be an immediately feasible approach since the Indian Government is yet to permit growing of genetically modified crops. Till that time, one can explore gene editing and CRISPR-cas9 technologies to develop herbicide resistant cultivar (Rich *et al*. 2004; Haussmann 2004; Makaza *et al*. 2023).

Conclusion

Global climate change has already resulted in several uncertainties in agriculture production. More or less precipitation and increased temperature are certain and order of the day in future. These events are going to be much more frequent and intensive in the future that questions the capability of sustaining food production for ever increasing global population. Weed management also seems to be more crucial in days to come under climate change scenarios to sustain food production because increased CO_2 and high temperature tend to favor growth of weeds (C_4) compared to crops (C_3). This scenario is not different either with the production of millets, which are suggested to be substitutes for cereals. Because millets were hitherto considered as poor man's crops not given as much attention as in the case of cereals in managing and attaining higher productivity. In recent years, they are paid attention not only to sustain hunger but also to meet nutritional requirements since they are richer in protein (pearl millet), minerals, vitamins and antioxidants than cereals. Millets are C_4 similar to weeds, hence they can compete and thrive under climate change scenarios better than C_3 cereals. They are considered an alternative crop for the climate change condition. In fact many farmers in India already switched over to short duration, less water requiring and climate change resistant millet crops over rice, wheat and corn. Limited information suggests the herbicide application is crucial to manage weeds even in millets notwithstanding the environmental impact. Task before scientists is not only to develop herbicide resistant crops but also avoiding development of resistance in weeds. A comprehensive research program is required to understand the biology and distribution of weeds under climate change and the efficacy of herbicides to control weeds in millet crops and it is very crucial to sustain the future grain for human population.

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