Review Article

Revitalizing the Potential of Minor Millets: Agrarian Constraints, Possible Solutions and Future Roadmap

ABSTRACT

In contrary to the recent revival of millets like sorghum & pearl millet globally, one segment of millets is still neglected mostly in spite of their massive nutritional benefits and complementing effect on ecology; these are referred as minor millets collectively. The focal causes of its underrecognition include lack of awareness among the consumers about its vast potential utilities and multifaceted constraints acting together to curb down its production pattern. Lack of effective research and development in the area of crop improvement via breeding and biotechnological interventions is holding back its upswing. There is very little comprehensive documentation available on these dynamics of minor millets. This paper studies those critical limiting factors while also prescribing the way out to ensure nutritional security and environmental sustainability.

Keywords: small millets, proso millet, foxtail millet, kodo millet, barnyard millet, little millet, browntop millet, international year of millet

1. INTRODUCTION

Minor millets are an agronomic community of small seeded coarse-grained food crops under family Poaceae excluding Sorghum and Pearl millet. It includes Foxtail Millet (*Setaria italica*), Proso Millet/ *Cheena* (*Panicum miliaceum),* Kodo Millet (*Paspalum scrobiculatum*), Barnyard Millet / *Sanwa* (*Echinochloa crus-galli*), Little Millet/ *Kutki* (*Panicum sumatrense*), Browntop Millet (*Brachiaria ramosa*), Job's Tear (*Coix lacryma-jobi*), Fonio (*Digitaria exilis*) and Teff (*Eragrostis tef*). The term 'minor' reflects the fact that these grains are neglected in terms of any significant commercialization, acreage, production, consumption and research investment.

From times immemorial, minor millets have been an integral part of our culture as mentioned in principle ancient texts such as Kautilya's *Arthashastra*, *Ain-i-Akbari* etc. However, the aftermath of green revolution pushed these minor millets into the abyss. The area declined drastically from 2.44 Mha in 1990-91 to 0.45 Mha in 2019-20 and the production shrinked from 1.19 M tonne to 0.37 M tonne [1]. But lately, there is an evident paradigm shift as a result of evolved health consciousness among the consumers and its potential impact towards environmental sustainability. Minor millets are preferred over staple cereals due to their superior nutritional quality, low glycemic index, gluten free nature, competency to combat climate change, adaptability in low-input high-stressed agroecological conditions. In the avenue of unleashing its huge potential, there are certain obstacles at both land and lab levels. This paper specifies those constraints and also broadens the horizon of crop improvement by suggesting promising prospective interventions and the way forward.

2. UTILIZATION

2.1 Minor Millets as Crop Models

Studies show that exogenous application of Selenium in Foxtail and Proso millet has several encouraging results, especially in terms of growth stimulation, increasing biomass and photosynthetic pigments which can be used as a model for studying salinity stress at different stages of crop growth [2]. Another major breakthrough comes from the recent work by Yang & colleagues led to the development of *Xiaomi*, a Foxtail Millet mutant with fully known genome sequence (2n=2x=18), efficient transformation, short growth cycle and tiny plant dimensions as an ideal C4 plant model for studying various cellular, molecular, biochemical and physiological traits [3].

2.2 Minor Millets as Baby Food

Millets are well stocked with antioxidant phytochemicals, have a low glycemic index & are primarily alkaline [4]; thereby, promoting body health & providing a more diverse food basket for nutritional improvement. Proso millet is rich in lecithin which keeps the nervous system healthy. It also has the highest amount of phosphorus amongst all other millets essential for cell growth and development as well as for good immunity. Barnyard millet is rich in Iron that keeps Anaemia at bay. Little millet is rich in Phosphorus and good cholesterol, suitable for weight gain in babies. Foxtail millet has higher protein content than wheat and also has 30 times richer fibre content than rice. Healthcare experts disapprove of polishing and extensive processing of millet grains as their nutritional quality will then be put at risk.

2.3 Minor Millets for Biofuel Production

Studies have yielded encouraging results which support the use of foxtail millet as an alternative lignocellulosic feedstock for bioethanol production [5]. A comparative study of Barnyard millet, Foxtail millet & Little millet revealed that the husks of all three can be used to produce bioethanol; however, the concentration of bioethanol observed was greater in Barnyard millet husk [6]. On the other hand, Proso millet & Maize have similar starch content with fermentation efficiencies ranging from 84% to 91% whereas it was observed to be 97% in waxy type lines [7]. This proves that Proso millet has high potential to be used in fuel ethanol production.

2.4 Minor Millets in the Indian Food Basket

Minor millets have always been a culturally important part of our diet for centuries and are commonly consumed in the form of *roti, khichdi, upma, dosa,* puddings or cake. These traditional preparations possess antimicrobial, antioxidant, probiotic and prebiotic properties. Barnard & Little millet are specifically consumed during fasting [8]. In some tribal areas, grains of foxtail millet is cooked as millet rice or consumed as '*sargati*' (a stiff porridge); sprouted millet grains are used as vegetables whereas, in Uttarakhand, Barnyard millet is consumed as '*paleu*' or '*chencha*', a thick sticky savory dish [8]. Barnyard Millet is also used to make kheer & halwa. '*Juma*' is a treasured recipe of *Lahaul Spiti* wherein sheep intestine is stuffed with spiced millet flour, steam cooked and served with piping hot mutton soup [9]. Kodo millet can also be used as rice substitute.

2.5 Minor Millets as animal feed & fodder

Foxtail millet seeds have been used as bird feed and for fodder [10]. Barnyard millet has a high straw yield and fodder value even at multiple cuttings [11] (about 6.3 tons/ha) which is rich in protein (7.6%), dietary fibre (23%), ash (12%) and fat (2.0%). Proso millet combined with oats is used as a starter for calves. Its grains are pelleted with other grains for feeding multiple types of poultry. Ground Proso millet is used as lamb fattening feed and is also used in dog and hamster food.

2.6 Other Non-Conventional Uses

Millet hulls, the by-product remaining after dehulling of millet grains, is sometimes used as a filling material (as in pillows) due to their high fibrous content [12]. Barnyard Millet starch is rich in amylose and is used in combination with borage seed oil for manufacturing biodegradable films or biofilm packaging material which are resistant to microorganisms and prevents free radical formation [13]. Aqueous extract of *E. colona* can be used in biosynthesis of Silver nanoparticles as a safe and eco-friendly approach for use of nanoparticles at a large scale in varied fields such as medicine, agriculture, forensics, biotechnology, engineering etc [14]. A broad-spectrum antifungal peptide, EcAMP1 has been identified in the seeds of Barnyard millet (*E. crus-galli*) which can be used in the synthesis of novel antimicrobials through protein engineering [15].

3. MINOR MILLETS FOR SUSTAINABILITY

3.1 Climate Resilience

Climate change is already having an impact on agricultural production, food stability and nutritional security in a number of countries specially in developing countries. Up surging temperatures, unpredictable rainfall patterns and continued droughts occur during critical crop phases, resulting in shorter grain filing periods, subordinate yields and diminished biomass. On top of that, high temperatures encourage speedy evaporation, which dries out the soil and makes it more difficult for plants to get enough water, reducing their ability to absorb nutrients. Because the importance of small millets is becoming more widely recognized [16]. Millets are well known for their climatically resilient characteristics, which include adaptability to a wide range of ecological conditions, reduced irrigation requirements, improved growth and productivity under low nutrient input conditions, reduced reliance on synthetic fertilizers, and low vulnerability to environmental stresses [17].

3.1.1 Physiological benefits

Millets have a number of biochemical, morpho-physiological and molecular characteristics that make them more resistant to environmental strains than cereals. Millets have a shorter life cycle (12-14 weeks from seed to seed) than rice and wheat, which can take 20-24 weeks. This assists people in avoiding stress. Short stature, thickened cell walls, small leaf area and the ability to form dense root systems, on the other hand, mitigate the prevalence and effects of stress conditions [18]. Millets benefit from the C4 photosynthetic trait as well. Carbon dioxide (CO_2) is concentrated in the C4 system around ribulose-1,5-bisphosphate carboxylase/oxygenase (RuBisCO), inhibiting oxygenation and photorespiration of ribulose 1,5-bisphosphate (RuBP) [19]. As a result, the C4 mechanism increases the concentration of CO_2 in the bundle sheath, which reduces photorespiration and increases the catalytic activity of RuBisCO in plants. Millets have increased photosynthetic rates in warm climates, resulting in instant water use efficiency (WUE) and nitrogen use efficiency (NUE) that are 1.5-4 times higher than C3 photosynthesis due to RuBisCO of C4 plants working in elevated CO_2 levels [20]. Millets benefit from C4 photosynthesis in addition to WUE and NUE, including improved ecological enactment in warm climates, more flexible biomass allocation patterns, and lower hydraulic conductivity per unit leaf area [20]. These qualities of millets make them next-generation crops with the potential to be studied in terms of the characteristics of climate-resilient plants and used to enhance major cereals.

3.1.2 Low Carbon Footprint

Wheat emits the most greenhouse gases of any major cereal crop, at approximately 4 tonnes CO_2 eq/ha, followed by rice and maize (at approximately 3.4 tonnes CO_2 eq/ha). Millet has a low carbon footprint per hectare of 3,218 kilograms, which contributes to mitigating climate change. Millets have the lowest carbon equivalent emission (CEE) of any crop (878 kg C ha1) [21].

3.1.3 Drought adaptability

Certain strategies are devised by minor millets to withstand drought conditions which makes it a perfect crop for dryland agriculture. In case of little millet, shoot length is decreased but root length is increased under moisture stress conditions along with significant accumulation of antioxidants, Reactive Oxygen Species (ROS) scavenging enzymes, superoxide, catalase, glycine betaine (GB) & increased concentration of total free amino acid [22]

3.2 Effect on Soil

Several researchers have studied and demonstrated that millet cultivation influences the soil health and fertility positively. A study revealed that after 5 years of monocropping Proso millet, the soil had higher levels of total nitrogen, available nitrogen, phosphorus and potassium than the soil in which common buckwheat and common bean were cultivated [23]. Millet based farming system is proved to be a sustainable approach to improve soil health and soil organic matter content [24]. Such farming practice improve soil physical properties and enhance soil water holding capacity which is beneficial in rainfed areas [25, 26]. Millets with deep rooted system improve physical characteristics of soil such as soil compactness, soil porosity and soil aggregation and also enable them to asses moisture and nutrients from the deeper soil layers, making them drought tolerant crops [27]. Intercropping millets with legumes can improve soil organic carbon, soil aggregate stability and soil microbial activity which are key indicator of soil health [26]. Minor millets with nitrogen fixing ability can contribute to soil fertility by improving nutrient availability and physiochemical properties [28]. Millet cultivation can also check soil erosion as dense root system holds soil compactly [29]. Overall, Minor millet inclusive farming system have significant positive impact on soil health, making it an essential crop for sustainable agriculture practice in different regions.

4.0 CONSTRAINTS

4.1 Constraints in the Pathway of Genetical Improvement

The narrow genetic base is one of massive barrier in the way of minor millet genetic improvement. If we talk about small millets germplasm conserved in gene banks, Foxtail Millet has highest germplasm conserved (44761) while Guinea Millet has least (3). Conservation of germplasm is essential before losing them forever [30]. Availability of Genome sequencing is crucial for the possible genetic improvement in any crop. Among small millets, only Foxtail Millet has complete annotated genome sequencing available whereas Proso Millet and Barnyard Millet has draft genome sequencing; but no genome sequencing is there for Little Millet and Kodo Millet [31].

4.2 Constraints in the Pathway of Biotechnological Improvement

Due to regional or economic factors, biotechnology-based minor millets improvement has been limited. Production is increased by the conventional breeding methods for selection and controlled hybrid and there are already cultivars available which are resistant to biotic and abiotic stresses. That is the reason of neglected improvement in the novel traits of minor millet [32]. Productivity of the minor millet is very low than major millets and cereals and that could be related to cultivating environment and practices [33]. Due to challenges with plant regeneration and subpar transformation efficiency, biotechnology of minor millets has trailed behind that of the major cereal crops. The responsiveness of millets to transformation methods is still quite low. For any of the millet species, there are not any model cultivars that can transform at an efficient rate [32].

4.3 Constraints Related to Insect Pests

Insect pests can cause significant damage to these crops, resulting in reduced yields and financial losses for farmers. There are over 150 species of insects worldwide that feed on millets, with 116 of them being found in India [34, 35]. Insects attack and damage millet crops at different growth stages of the plant, resulting in lower production, declining productivity, and poor-quality grain [36, 37]. In India, insect attacks account for 10–20% losses in yield in millets [38]. Minor millets are more often attacked by shoot flies, stem borer, armyworm, termites, and the grain weevil. One of the main pests that affect millets is the shoot fly. There are many species of shoot flies (Diptera: Muscidae) that attack different types of minor millets in India [39]. It is a very destructive pest that results in considerable losses in yield. During the seedling stage, larvae cut the growing point, which results in a dead heart, and at the reproductive stage, they consume ear heads and destroy panicles [40].

The stem borer is a moth with a filthy, brownish appearance that is mostly active at night. Caterpillars consume leaves, bore through stems to cause dead hearts, and dig into ear heads. It damages the crop starting in the second week after germination up to crop maturity. The early instar larvae eating in the whorl are what generate the irregularly formed holes on the leaves. A central shoot's drying, which results in "dead hearts", is seen and there is also significant stem tunneling. Tunneling of the peduncle causes it to shatter, which causes whole or partial chaffy panicles [40]. The armyworm is a polyphagous pest that attacks many crops, including millets. The larvae feed on leaves, stems, and ears, causing defoliation and yield losses. Termites are a social insect that lives in underground colonies and attacks both young seedlings and mature plants. Plants that are infected droop and eventually die. The grain weevil is a common pest of stored millet grains. The adults lay eggs on the grains, and the larvae feed inside, causing damage and reducing grain quality.

5. POTENTIAL SOLUTIONS AND FUTURE ROADMAP

5.1 Breeding Objectives

Glutinous (waxy/sticky) varieties are comparatively more preferred by consumers for the Foxtail Millet and Proso Millet. To detect the waxy genotype, specially designed molecular markers are required [41]. The wild species should be studied beyond only the weed science point of view. Cyclopiazonic acid, produced in Kodo seed inflected by *Aspergillus flavus* and *A. tamarii* is responsible for the 'Kodua poisoning' in man and animals [42]. The breeding target should be to develop variety resistant to these two fungi. For orchards and agro-forestry, shade tolerant varieties should be the target [30]. Grain loss due to lodging is a major problem in Kodo Millet which can be overcome by improving culm strength [43]. Breeding for larger seeds is helpful to improve milling recovery in small millets [44]. Growers don't prefer additional intervention to control diseases for obvious economic reason; thus, particularly for orphanage crops like minor millets, use of disease resistant varieties is advantageous. A list of already developed resistant varieties against major diseases of different minor millets is provided in Table 1.

Table 1. Resistant Varieties/ Entries in Minor Millets

Crop	Disease	Causal Organism	Resistant Varieties/Entries	Reference
BARNYARD MILLET	Head Smut	*Ustilago crus-galli*	ABM 4-1, VL 207, VL 208 PRJ 1	[45] [46]

	Grain Smut	*Ustilago panici-frumentacei*	PRB 402, S 841, TNAU 92, VL 216, VL 219 PRB 901, PRB 903, TNAU 141 and TNAU 155	[45] [47]
FOXTAIL MILLET	Rust	*Uromyces-setaria italicae*	SiA 3164, SiA 3205 DHFtMV 2-5, SiA 3221, TNSI 266, SiA 3156, SiA 3164	[48] [49]
	Blast	*Pyricularia setaria*	SiA 3164, SiA 3205 DHFtMV 109-3, DHFtMV 2-5, DHFtMV 55-3, SiA 3223 SR 118, SR 102, ISc 709, 701, 703, 710, 201, JNSc 33, 56, RS 179 Foxtail- 49, 96, 132, 160, 200, 237, 267, 295, 362, 364, 663, 717, 774, 784, 838, 936, 1013, 1037, 1137, 1162, 1665, 1725, Check SIA - 3156.	[48] [49] [50] [51]
	Banded Blight	*Rhizoctonia solani* kuhn.	SiA 2863, ISC 74 VFMC-391	[52] [53]
KODO MILLET	Head Smut	*Sorosporium paspali*	KMV 8, KMV 20, JK 41, JK 62, JK 65, JK 106, JK 13	[54]
	Udbatta	*Ephelis sp.*	IPS 45, 196, 342, 365, 368, 381, 387, 140, Niwas 1	[55]
PROSO MILLET	Leaf Spot	*Bipolarispanici-miliacei*	RAUM-7	[56]
LITTLE MILLET	Grain Smut	*Macalpinomyces sharmae*	DPI 2386, DPI 2394, PLM 202, OLM 203, CO 2	[57]

5.2 Genetic Intervention

For improvement under adverse condition, priority traits for breeding should be incorporated [41]. Comparative genomic approach can be applied efficiently for gene mining and identifying molecular markers. As several small millets lack complete genome sequencing, genome of conventional crop can be used for study [31]. 16 genotypes (TNPSc 86, TNPSc 155, TNPSc 217, Podivaragu, Adari, Pacheri etc.) are reported which can be utilised to improve culm strength in Kodo Millet [43]. Interspecific hybridization can be a promising pathway towards genetic enhancement. The F1 as a result of Interspecific hybridization between Japanese and Indian barnyard millet shows improved plant height, high culm branching and increased number of tillers in comparison to its parents [58]. MutMap+ can be used to identify genomic regions associated with various biotic and abiotic resistance [44]. The availability of Online Genomic Database for minor millets is important for further research related to crop improvement. Some of the available genomic databases are - Millet Genome Database, Setaria italica Genome Database (SiGDB), Foxtail Millet Marker Database (FmMDb), Foxtail Millet MicroRNA Database (FmMiRNADb), Foxtail Millet Transcription Factor Database (FmTFDb), Foxtail Millet Transposable Elements-Based Marker Database (FmTEMDb) [59].

5.3 Biotechnological Interventions

The goals of improvement of minor millets using biotechnology include improved use of natural resources, biotic and abiotic stress resistance development, and quality enhancement for increased consumer acceptance.

5.3.1 Improving Productivity

One of the key physiological elements contributing to plant productivity is a characteristic relating to photosynthesis [60]. The primary characteristics that affect photosynthetic capability at the level of the entire plant are the canopy architecture, leaf morphology, and vascular architecture. Although little research has been done on this topic, it may be possible to increase agricultural photosynthesis and, eventually, production by understanding the genetic diversity in traits associated to photosynthesis in both crop and wild species [61]. Organelles involved in light perception, gene expression, the manufacture of lipids, pigments, and proteins, and the expression of numerous transporters must work closely together at the cellular level. A full understanding of the physiological underpinnings of the developmental features is necessary to engineer them in order to increase photosynthetic efficiency and, consequently, yield. Understanding the above-mentioned mechanism in model species and important cereal crops has advanced quite a bit. There are, however, few instances of this comprehension in small millet [62].

5.3.2 Transgenic plant improvement

Minor millet has less regeneration and transformation efficiencies [63]. Though transgenic plants were produced by particle bombardment of foxtail millet pollen and inflorescence, but the transformation efficiency was low [64]. For gene transfer use of Agrobacterium is more efficient than the biolistic gun. Agrobacterium mediated transformation can produce a high number of stable and low copy number transgenic events with fewer DNA rearrangements, transfer larger DNA segments into recipient cells and transgene expression is more stable over generations than with the direct gene transfer method [65]. Using this improved transformation technique, the SBgLR gene, which encodes a lysine-rich protein from potato (*Solanum tuberosum* L. cv. Desiree), was effectively introduced into Foxtail millet cv. Jigu 11.

5.3.3 Future Prospects

Investigation has been going on changing in protein quality and quantity in minor millets. Studies required on the effect of processing methods on the biological functions of millet protein. There is little information about the changes in physiological, biochemical, and structural characteristics associated to photosynthesis in small millets, thus more research is required for increasing the productivity of small millets [62].

5.4 Insect Pest Management

The late-sown crop is more commonly infested. One of the simplest and most cost-effective ways to control it is to seed early when the monsoon begins. It can be controlled by adopting cultural practices such as timely sowing, maintaining proper plant spacing, and intercropping with legumes or non-host crops, which can help reduce the impact of shoot fly in little millet [66]. Chemical control measures such as the use of insecticides can also be effective in managing shoot flies in minor millets. Use of imidacloprid (Confidor 200 SL) at 0.5 mL/L or thiamethoxam (Actara 25 WG) at 0.3 g/L has been found effective against shoot flies in minor millets [67].

Stemborer can be managed by removing and destroying the stubble of the previous crop and by slicing the stems to stop it from further spreading. Biological control measures such as the use of natural enemies can be effective in managing stem borer in millets. Research has shown that the use of egg parasitoids such as *Trichogramma chilonis* and *Bracon brevicornis* can effectively control the stem borer population in millet [68]. Chemical control measures such as the use of insecticides can also be effective in managing the stem borer in millets. Research has shown that the use of insecticides such as carbaryl and quinalphos can effectively control the stem borer population in millets [40].

Cultural practices such as crop rotation, early planting, and timely harvesting can help reduce the armyworms population. Insecticides such as Chlorpyrifos, Spinosad, and Emamectin Benzoate are also effective in controlling armyworms [69]. Cultural control measures such as deep ploughing and crop rotation can help reduce termite populations. Deep ploughing can expose termites to predators and reduce their numbers. Crop rotation with non-host crops can also help to reduce the incidence of termite infestation. Irrigate the crop when there is low moisture in the field. In areas where termites are prevalent, using chlorpyrifos at 1–1.5 mL per liter of water is recommended for termite control [70].Proper storage practices such as cleaning, drying, and fumigation can help storage infestation. Grain weevils thrive in warm temperatures, so it's important to keep the stored millets in a cool, dry place. The ideal storage temperature for millets is around 10°C to 15°C [71].

6. GOVERNMENT SUPPORT

The Department of Agriculture and Farmers Welfare (DA&FW) is implementing a Sub-Mission on Nutri-Cereals (Millets) under National Food Security Mission (NFSM) to enhance area report, production & productivity of millets [72]. There has been survey conducted to know the inclusiveness of minor millets and its accessibility to millets-based offerings, various states are conducting campaigns. In Odisha, Odisha Millet Mission (OMM) launched in 2018 aims to revive millets in 15 districts; in Karnataka, they have launched initiatives for Millets as “The Food of the Future” with incentive to farmers Rs. 10000/ha for cultivation of millets. They are also encouraging organic farming & millet promotion through “Savayava Bhagya Yojana”. To endorse and create awareness, they organized National and International trade fair [73]. In order to promote millets, Chhattisgarh state is the only state where Kodo, Kutki and Ragi are being procured at Minimum Support Price (MSP); Kodo-Kutki is being procured at Rs 3,000 per quintal to help the tribal and other farmers of the state [74].

The Government of India has taken certain initiatives to promote Minor Millets throughout the nation such as Initiative for Nutritional Security through Intensive Millet Promotion (INSIMP) under Rashtriya Krishi Vikas Yojana (RKVY), Rainfed Area Development Program (RADP), National Food Security Mission (NFSM), National Nutrition Mission (NNM) etc. The Integrated Child Development Services (ICDS) and the Mid-Day Meal Scheme (MDMS) have included minor millets in their menu to promote their consumption among children to combat malnutrition and hidden hunger. The government also plans to set up Centers of Excellence for bringing these ancient crops to the centerstage.

7. CONCLUSION

The revitalization of minor millets holds mammoth potential for addressing the urgent issues of global food security, environmental sustainability and climate change. In order to unleash its complete potential, Minor Millets should be utilized in a multidimensional way for satisfying the holistic needs. To disseminate its awareness extensively, genuine efforts need to be made by all the actors of the ecosystem. Conferences, symposiums and seminars should be organized frequently to integrate the minds of policy makers, stakeholders & researchers. The government should encourage the creation of entrepreneurial ventures in the field of minor millets. For addressing the neoteric agrarian challenges, minor millets can play a pivotal role by intensifying the cropping system as a cover crop, catch crop or inter-crop. Both conventional breeding methods and biotechnology should be employed parallelly for achieving maximum crop improvement. The emphasis should be on developing male sterility line, mutation breeding, genomic assisted breeding, proteomics, metabolomics, Agrobacterium-assisted transformation etc. The roadmap for the future must be built on the foundation of research, innovation and policy support to ensure a sustainable future for all.

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