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REVIEW ARTICLES

Barnyard millet (*Echinochloa* spp.): a climate resilient multipurpose crop

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Abstract
Crop diversification can help to reduce the existing pressure on agriculture and to meet food requirements of the mushrooming population. Millets are a viable choice for sustainable agriculture and belong to underutilized crops limited to smallholder farmers. Cereals such as barnyard millet are bestowed with superior nutritional profile and can better withstand biotic and abiotic stress conditions. Although they occupy a lower position as a feed crop, braving the worst sets of odds these are to the far best suited crops to cope up with the vagaries of climatic conditions and thus can promise safe agricultural future and nutritional security of the world. This review highlights importance of millets with major focus on "Barnyard millet". It is one of the hardiest multipurpose crop with wide adaptability to adverse climatic conditions. It is regionally abundant but globally rare, scientific knowledge is also scant about its genetic resources and thus it is facing limited use relative to the potential benefits it can offer. Its remarkable climate resilient properties make its survival easy in harsh and fragile environments as it require minimal agricultural inputs. Germplasm of barnyard millet can prove to be a reservoir of unique alleles to the breeders. Despite of its enormous potential, the crop has not gained popularity among masses. Conserving traditional biodiversity compounded with modern genomic tools can accelerate its production and fill the yield gaps thereby promoting sustainable cropping practices and growing crops best suited to the respective regions, instead of forcefully changing the cropping pattern. Efforts are needed for enhancing its cultivation and acceptance nationwide as a cereal occupying common food basket. Review highlights nutritional quality, stress tolerance and antimicrobial properties of *Echinochloa* spp. Besides, constraints limiting its production, breeding objectives, germplasm collections and efforts required to promote its acceptance worldwide are also highlighted.

Keywords Barnyard millet · Food security · Climate resilient · Crop diversification · Sustainable agriculture · Orphan cereal

Introduction

By 2050, an increment in food production is required to feed a population of 9 billion people, according to the target set by world summit on food security (Beddington 2010; Tester and Langride 2010). Increasing food demands compounded with global climatic change is altogether putting pressure on agriculture production worldwide, under such conditions major advancements have to be made to scale up the production in limited land resources which can be done by either changing crop consumption pattern or expanding cultivation in natural lands. However, increasing the production is not a mere goal of food security, but it is also important to provide people with nutritious and healthy food in sufficient amount to meet their dietary requirements especially in developing

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countries like India where hunger and poverty are deep rooted problems that need to be looked into.

Plants are constantly exposed to a variety of stress conditions and survive at physiological cost that may hinder plant growth and development thereby reducing the yield (Trivedi et al. 2017). Erratic climatic conditions like rising global temperature, drought, floods, and water scarcity are the major challenges that agriculture sector is facing and this scenario will be worsening in future (Allen and Ingram 2002; Meehl et al. 2007). Under such conditions relying on few crops and maintaining sustainable agriculture would not be possible thus there is a requirement for exploring diverse crops with useful agronomic and stress tolerant traits.

Excessive production practices is causing a load on major staple cereals, thus there is a need for alternative nutritional food source and crop diversification amidst aforementioned challenges. Millets can prove to be an economically viable substitute for major staple food crops to cope up with the food shortage, maintaining nutritional security and dietary diversity at the same time. "Millets are one of the oldest foods known to humankind and possibly the first cereal grain to be used for domestic purposes" (Michaelraj and Shanmugam 2013). These are nature's gift to poor farmers with limited resources. While pearl millet (*Pennisetum glaucum*) is the most widely grown, finger millet (*Eleusine coracana*), foxtail millet (*Setaria italica*), kodo millet (*Paspalum scrobiculatum*), proso millet (*Panicum miliaceum*), barnyard millet (*Echinochloa* spp.), and little millet (*Panicumsum atrense*) are a group of genetically diverse, low input requiring climate-smart small seeded cereals that occupy secondary group known as 'small millets' and are well adjusted to diverse ecological situations (Goron and Raizda 2015). Among these, barnyard millet also called as billion dollar grass, jhangora, sawan and madira has gained immense importance for its dual purpose use as feed and fodder crop. It belongs to the family *Poaceae* and has an ability to perform better under severe conditions of drought, salinity, heat, and floods compared to other cereal crops (Gupta et al. 2010; Prabha et al. 2010).

Unlike rice, maize and wheat that are preferably grown on fertile lands, crops like barnyard millet are grown in poor marginal areas as least care is taken regarding their cultivation. Persisting climatic changes and stressful environmental conditions interfere with plant's successful reproduction and survival and thus plants which are able to cope up with these challenges can prove to be decisive for food security. Despite of all the advantages, millets have been neglected and a steady decline has resulted in their cultivation over decades (Padulosi et al. 2015). Barnyard millet has an enoromous potential to be a major staple crop but it still remains underexplored and is confined to its regional importance only as little attention is given to collection and conservation of its diversity. It is generally grown in hilly areas with rain fed conditions, fluctuations in temperature and suffer vagaries of weather. It is traditionally grown and consumed by subsistence farmers for food and fodder in Japan, Korea, India and China and valued for its tolerance to mainly drought and flooding stress (Upadhyaya et al. 2014). It has high nutritional value, matures readily and produce voluminous fodder as well. Despite of its unique agronomic and nutritional traits, it is unfortunate that there is lack of genetic resources for any of the domesticated species of this crop and remains most under researched crop in comparison to other cereals (Trivedi et al. 2017).

Efforts are required to develop genomic resources for this crop. Utilization of high-throughput approaches for genotyping and using available genomic resources of taxonomically closest species can be useful in crop improvement practices for barnyard millet (Singh and Upadhyaya 2016). There is a need to screen agronomically important traits and conserve the desirable germplasm for climate resilient crop improvement practices and promoting cultivation of such crops in other similar regions with marginal landforms and erratic climatic conditions. Thus directing research to barnyard millet and related crops would be a viable choice to overcome the obstacles in food and nutritional security. Studies so far on this millets has been confined on diversity analysis of seed banks and collection of germplasm, studies on genetic level is still lacking that are important for development improved varieties that could prove a boon to food and nutritional security of global population. These underexplored crops were initially utilized by rural smallholder farmers, thus their market development is also limited and has to start from the production base itself. These crops face limited demands and are uncompetitive in comparison to existing cash crops with well established demand. Application of modern genomic methods compounded with traditional knowledge is required to increase their consumption and acceptance in the market. Nutritional benefits compounded with their ability to grow under stressed conditions outweigh drawbacks regarding their low yield and poor economic performance. Landraces of these crops needs to be preserved in seed banks for their conservation. The pace at which genetic advancements are being made in this crop are very slow contributing to its reduced yield. It is getting marginalized and losing its importance as a feed crop globally (Sood et al. 2020). This review highlights nutritional, vegetative and stress tolerant traits of barnyard millet. Figure 1 summarizes nutritional and stress tolerant traits in barnyard millet. Studies so far done on this crop and constraints in its production and marketing are also highlighted along with the efforts to promote it as a superior feed crop.

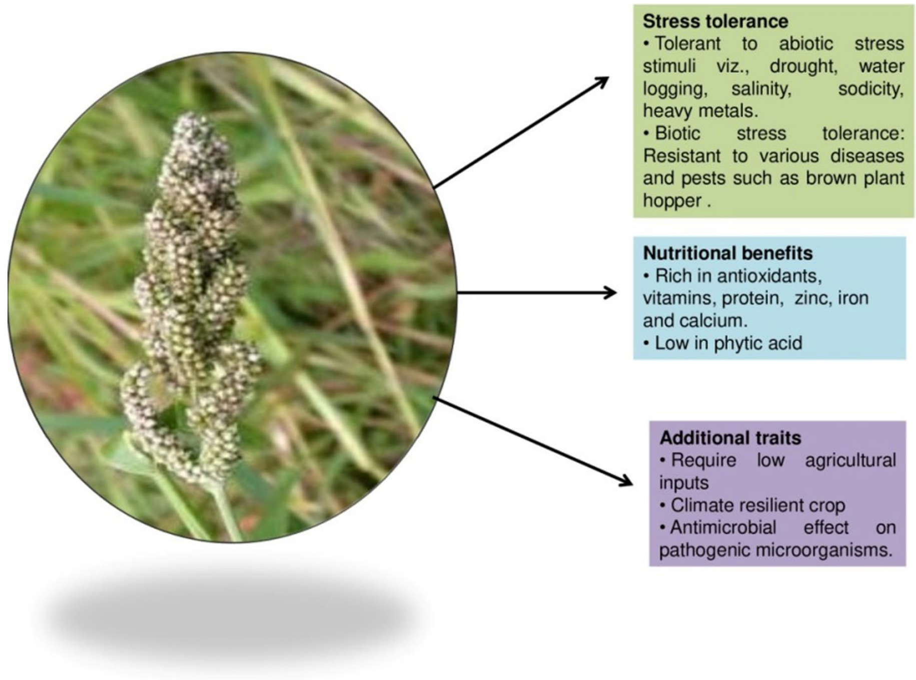

Fig. 1 Pictorial presentation of beneficial traits of barnyard millet

Small millets: neglected crops

All the small millets have an old cultivation history, going behind 3000–5000 years and occupy a unique position in hill agriculture, these are the crops of small and marginal farmers and are nature's nutraceuticals. Millets are hardy grasses with short growing season, these thrive well in dry zones and marginal lands and can produce harvest just within 65 days from day of sowing under optimized storage conditions. Seeds can be stored up to two or more years (Michaelraj and Shanmugam 2013). Millets are used as staple food in many countries. For instance in Niger it represents 75% of total cereal consumption and in Namibia and Uganda it represents 25% and 20% of total cereal consumption, respectively (Leder 2004). Small millets are defined as slender grassy plants cultivated for their small grains with nutrient rich properties. Although, these crops are grown globally, they still do not occupy dominant position in food basket because of the position being occupied by common staple crops such as wheat, maize and rice. With diverse adaptations these crops play an important role in food and nutritional security in rural households. Out of six small millets grown in India, finger millet, barnyard millet, foxtail millet and proso millet are grown exclusively in Himalayan region at present. Little millet, though used to be grown earlier in some areas, is presently out of cultivation (Rawat et al. 2018).

Diversity and area under cultivation of Barnyard millet is also fastly depleting. In a report from Garhwal Himalayas 72% reduction in cultivated area has been observed for barnyard millet (Maikhuri et al. 2001). Area dedicated for cultivation of this crop has fallen down in past 50 years, but due to its ability to survive harsh conditions, it still remains crop suitable for climate resilient agriculture (Sood et al. 2015).

Inadequate efforts have been made for developing high yielding cultivars for this crop. Besides, lack of modern processing technologies and little scientific attention has pushed these cops to marginal and sub marginal areas. Small millets faced a lot of unfortunate consequences over time as all the policy-makers and research practices kept millets largely out of the scope. Hence, they have been termed “orphan cereals” which indicate their position with respect to staple food crops (Goron and Raizada 2015). These crops can grow in most inhospitable conditions, where no other crop can be grown and thus are ideal in an era of climate change and steadily depleting natural resources (Padulosi et al. 2015). Their long storability under ordinary conditions has made them "famine reserves" which accounts for a major aspect with respect to Indian agriculture which is prone to vagaries of the monsoon. Being robust and climate resilient crops they can withstand the persisting scenarios. For instance, wheat, a major cereal of the common food basket is temperature sensitive that would fail to thrive. Rice on the other hand is known to release methane and thus would not be a viable choice under increasing global warming conditions. Thus to heal our planet millets, as a crop are suitable alternatives. These are cultivated worldwide as an important food and fodder crop in many regions, including Sub-Saharan Africa and South Asia. India being largest producer and accounts for 10.5 million metric tones (Kumar et al. 2016). Small millet cultivation in India is declining and that too with a rapid pace (Joshi 2013). Between 1956 and 2006, millet cultivation area have shrunk to 42% (Sateesh 2010). In India their cultivation extends from extreme southern tip at sea level to an altitude of 8000 feet above sea level in hilly areas of Uttarakhand and North-Eastern states (Michaelraj and Shanmugam 2013). Millets are grown by poor communities like adivasis and women from vulnerable communities in hilly and marginal areas with limiting resources thus know how of their cultivation also rests with these people only. These are never grown as mono crops but in integration with other crops like legumes, vegetables and oil seeds. Millets have various unique agronomic traits, these mature quickly, flourish well under rain-fed farming conditions and poor soils, and require considerably lower inputs than major cereals and thus make them crop of choice in marginal farming environments. Overall production of millets has however, increased from 7.7 to 10.7 Milion tonnes from 1961 to 2012, despite of this increase overall area dedicated to its farming has decreased over years (Padulosi et al. 2015). According to an estimate proposed by West and coworkers, increasing yields to "50% of the potential yield in all low-performing areas could increase annual production by 8.46 × 1014 kcal, which is enough to meet the basic caloric requirements of ~ 850 million people" (West et al. 2014).

Small millets are particularly neglected in terms of research and development. These constitute about 1% of the total grains grown all over the world, despite of the fact that these are well adopted to wide range of environmental conditions, mature quickly and survive under extreme climatic conditions (Mal et al. 2010). Out of all the millets Barnyard millet is the earliest maturing (Leder 2004). To improve agronomic and nutritional traits genetic manipulation is required and thus transformation and breeding studies that are presently confined to major crops are required to be extended to Small millets as well.

Barnyard millet (*Echinochloa* spp.) distribution and taxonomy

Barnyard millet (*Echinochloa* spp.) is one of the most under-researched and oldest known multipurpose self-pollinated crop to be domesticated in semi arid tropics of Asia and Africa (Sood et al. 2015). Barnyard millet is grown in many countries like India, China, Japan, Malaysia, East Indies, Africa and United States of America (Kumar and Prasad 2009).

In India, the crop is grown in Madhya Pradesh, Uttarakhand, Tamil Nadu, Andhra Pradesh, Karnataka and Uttar Pradesh where the cultivation of this crop covers an area of about 66.09 thousand ha and provides with an annual produce of 85.29 thousand tons (Channappagoudar et al. 2008; Yadav et al. 2010). It is the second most important among minor kharif crops in terms of acreage and production in hilly areas of Central Himalayas. In these regions, barnyard millet is a traditional crop and mainstay in diets of common people. It is grown in between the major crop seasons and can be useful in case of major crop failure (Kumar et al. 2007; Trivedi et al. 2017; Manimekalai et al. 2018). It is mainly cultivated in Uttarakhand that lies in North and in Deccan plateau region in the South (Dwivedi et al. 2012; Sood et al. 2015). However, its diversity and socioeconomic importance is eroding continuously among farming community in India (Joshi 2013; Maikhuri et al. 2001). Plant has gained attention as a fodder crop in countries like USA and Japan. It contributes around 11.5% of fodder consumption in Uttarakhand (India) (Sood et al. 2020). Barnyard millet is the mainstay of the diet and tradition of people living in hilly areas, this crop is extensively grown in central Himalayan region and have high regional importance (Kumar et al. 2007).

Genus *Echinochloa* belongs to the family Poaceae and includes 35 wild species. Majority of them are regarded as robustly growing weeds in cultivated fields and are aggressive colonizers of disturbed and barren habitats (Wanous 1990). Among all the millets it is fastest growing and can be harvested within nine or as little as six weeks of sowing (Wanous 1990; Prabha et al. 2010). The genus consists of two domesticated species namely *E. frumentacea* (Indian barnyard millet) and *E. utilis* (Japanese barnyard millet). *E. utilis* is grown in Japan, Korea and China while *E. frumantacea* is cultivated in India, Nepal, Pakistan and Central Africa (Yabuno 1987; Wanous 1990).

It is grown in hills with steep slopes. It can be grown upto 2300 m from mean sea level during kharif season and occupies special place in North western Himalayan states such as Uttarakhand in Garhwal Himalayas, providing assured harvest under harsh conditions. Its cultivation has also been substantially traced in North Eastern states (Gupta et al. 2009; Sood et al. 2015). Traditionally it was used as a substitute for rice in these areas (Kumar et al. 2007; Joshi 2013). It depends on natural precipitation and is a fast-growing annual summer crop. Rapid growth, drought tolerance and ability to grow in marginal environments make barnyard millet well suited crops in famine areas (De Wet et al. 1983). Both the species show a strong phenotypic similarity but are cytologically and genetically distinct. It is fastest growing crop, and give a satisfactory harvest and voluminous fodder even with low inputs and under harsh climatic conditions, these have high storability (Ugare et al. 2014). It is a staple cereal in land areas with climatic and edaphic conditions unsuitable for rice cultivation. Its straw is superior in comparison to rice, oat, or timothy straw in terms of protein and calcium content

(Sood et al. 2020; Poorniammal et al. 2021). This crop has a potential to provide nutritional security specially in hilly areas, it has highly nutritious grains and is rich in antioxidants. Despite of its enoromous potential, it still remains poor man's food and is not as popular as major staple crops among general masses.

Two domesticated species of barnyard millet despite of certain similarities, differ in certain characterstics (Table 1). Nonetheless, an advantageous quality of barnyard millet like other small cereals is that they continue to be grown in remote regions of the world which has preserved their biodiversity, and continue to hold their regional importance providing breeders with unique alleles for crop improvement.

Indian Barnyard millet (*E. frumentacea*)

It has been originated from its wild counterpart i.e. *E.colona also* known as "jungle rice". In India, *E. frumentacea* is grown along with foxtail and finger millet or sometimes it is present as weed in cultivated fields (Yabuno 1987; Gupta et al. 2009). Based on phenotypic traits such as length of flag leaf, plant height, and peduncles etc., *E. frumentacea* is divided into four races viz., *robusta*, *stolonifera*, *intermedia* and *laxa* (de Wet et al. 1983). Out of these four races, laxa is not so commonly found, it is endemic to Sikkim and thus more efforts are needed to be made for its collection (Gupta et al. 2009). It is mainly cultivated for food and fodder by hilly and tribal communities in rain fed regions where resources for crop diversification are scanty especially in Northwestern Himalayan regions. These crops offer benefits as they are easy to cultivate, produce voluminous fodder, has wide adaptability to stressed conditions and can complete its life cycle in a short time period. Molecular studies using RAPD markers suggest higher sequence diversity of Indian barnyard millet in comparison to Japanese species (Hilu 1994). Sequencing studies are lacking for this crop. It differs from *E.esculenta* and has whitish caryopses and smaller embryos (Sood et al. 2020).

Table 1 Difference in vegetative characterstics of two Indian and Japanese variety of barnyard millet (de Wet et al. 1983; Nozawa et al. 2006; Upadhyay et al. 2014; Sood et al. 2020)

Characterstic feature	Indian Barnyard millet	Japanese barnyard millet
Spikelets	Small and awnless	awned
Glumes	Membranous	Papery
Races	Four (*robusta*, *stolonifera*, *intermedia* and *laxa*)	Two (*utilis* and *intermedia*)
Wild progenitor	*Echinochloa colona*	*Echinochloa crus-galli*
Caryopses	white	Brown

Japanese barnyard millet (*E.esculenta*)

Originated from its wild counterpart, *E.crusgalli* and according to archaeological evidences has a history of domestication dating back to 4–5 millennia, as early as yayoi period in Japan (Sood et al. 2020), it differs from Indian barnyard millet morphologically, by its larger spikelets with papery glumes. The morphological and physiological diversity of Japanese barnyard millet such as flowering time, inflorescence shape, and spikelet pigmentation, and several other features, vary across landraces. This species is grouped into races like *utilis* and *intermedia* (Nozawa et al. 2006; Upadhyay et al. 2014). Molecular studies for Japanese barnyard millet, are done using SSR, RAPD, non-coding regions of chloroplast DNA and isozymes. Although less research is done on molecular level and sequencing data is also lacking for the species (Goron and Raizada 2015). It is cold stress tolerant crop and grow in areas with unsuitable climatic conditions for rice cultivation. But with adaptation of better agricutural practices and introduction of cold stress tolerant varieties of rice, a sharp decline was observed in Japanese barnyard millet cultivation. However, due to its nutritional and health benefits, it still remain crop of choice for consumption.

Morphological and vegetative characterstics of *Echinochloa*

Barnyard millet has two types of roots, viz., seminal and adventitious roots. Stem of the plant is usually hollow, may be simple or branched, with nodes and internodes. Stems can be hairy or devoid of hairs. Leaf of the plant is wide and flat, alternatively arranged on the culm. Plant produces panicles that are 10–25 cm long present at termini with different shapes ranging from cylindrical, globose to elliptical, panicle contains racemes with long spikelets that vary in colour from green, brown to purple these may be either crowded on one side or may be arranged around the rachis. Spikelets are enfolded by glumes, where uppermost glume consists of florets out of which lower ones are sterile and upper ones fertile. Fertile bisexual floret consists of three stamens and superior ovary with two plumose stigmas. Seeds are of small size with dimensions of 2–3 mm in length and 1–2 mm width, shape of the seed is round at base and pointed at apex and are enclosed within shining hard covering (Gupta et al. 2010, 2015; Gomashe 2016).

Nutritional qualities and food value of *Echinochloa*

The vast majority of India's population is so poor that they cannot afford even the least expensive balanced diets. Considering the nutritious aspects, barnyard millet is rich in protein, lipid, vitamin B1, B2 and nicotinic acid, it contains high amount of amino acids and radical scavenging polyphenolic compounds (Fig. 2). These grains are more nutritious than major cereal crops (Watanabe 1999). Unlike foxtail and porso millet, barnyard millet varieties are non glutinous. Barnyard millet has a mineral content ranging between 1.5 and 4%, its protein is easily digestible and it is an excellent source of dietary fiber. With lowest carbohydrate content among the millets, barnyard millet is recommended as an ideal food for type II diabetics. (Veena et al. 2005; Ugare et al. 2014). It is rich in micronutrients and proteins and thus can help in eradication of malnutrition that is common among growing children and women in developing nations thus it is highly recommended as a nutritional food for newborns and pregnant women (Underwood 2000). Indian barnyard millet when given to diabetic patients, significantly reduced blood glucose and LDL cholesterol levels (Ugare et al. 2014). Its straw makes a palatable and good quality fodder for cattle and is used for making hay and silage which is important in hilly areas where fodder becomes scarce during winters. It is also used as feed for caged birds. Performance of barnyard millet was recorded better for blood glucose, triglycerides, and cholesterol levels in rats as compared to other small millets like foxtail, kodo, porso and little millets (Kumari and Thayumanavan 1997). The grains of barnyard millet have lower phytic acid and high iron and calcium contents. These contain several functional constituents such as γ-amino butyric acid (GABA) and β-glucan that can be used as antioxidants and in reducing blood lipid levels (Sampathet al.1989; Kofuji et al.2012; Sharma et al. 2016). Its grains are cooked and consumed as idli, dosa, muruku and pudding, beverages by non affluent groups in various parts of world. Besides cooked items various edible food products are marketed as biscuits, sweets, flour, vermicelli etc. (Chandrasekara et al. 2012; Gupta et al. 2015). It is nutritionally superior to other cereals but still face limited utilization. Barnyard millet is an appropriate food for patients suffering from celiac disease and are intolerant to gluten, as patients cannot consume wheat or any of the millets closely related to wheat. It contains carbohydrate, protein, fat and crude fiber. It is a rich source of antioxidants, Zinc, calcium and iron (Manimekalai et al. 2018). Figure 2 represents the amount of aforementioned nutrient content of barnyard millet. Iron and fiber content of barnyard millet is higher than major cereals and other millets (Saleh et al. 2013). By eating millets, we will be encouraging farmers in dry land areas to grow crops that are best suited for those regions. Small millets have ability to lower plasma glucose concentration, insulin, adiponectin and tumor necrosis factor-a (Nishizawa et al.2009). The protein content of Japanese barnyard millet is twice as high as that of rice (Yabuno 1987). In case of allergic diseases like atopic dermatitis, grains of barnyard millet have been used as food materials in place of wheat and rice (Watanabe 1999). Besides, no major antinutritional compounds are present in this crop. Phytochemicals and dietary fiber has health beneficiary properties (Devi et al. 2014). Consumption of whole grains and their products are reported to reduce the risk of various life threatening diseases like cancer. Phytochemical content of whole grains is better than those obtained from fruits and vegetables together (Liu 2007). Whole grains are rich sources of

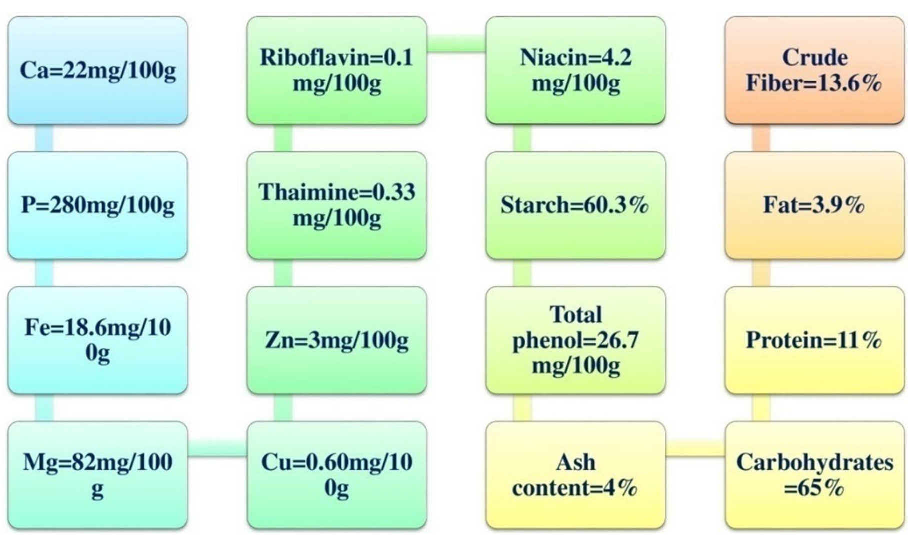

Fig. 2 Nutrient composition of barnyard millet grains (Manimekalai et al. 2018; Sood et al. 2020) Source: Chandra et al. 2016

polyphenols that show antioxidative and chelating properties. In a report, three antioxidative phenolic compounds were identified in ethanolic extract of Japanese barnyard millet out of which, one was serotonin derivative, and two were flavanoids (Watanabe 1999). The stover of barnyard millet is considered best in terms of nutritional qualities among the existing cereal stovers (Kumar and Prasad 2009). Thus, it has the potential to provide both food and nutritional security particularly in hills where nutritional deficiencies are abundant. Research needs to be done on metabolism and bioavailability of millet grains on human health and introduction of millet based products with better texture, processing and color.

Antimicrobial activity of barnyard millet

Extracts of millets are reported to show antimicrobial effect on various fungal and bacterial pathogens. For instance, seed coat extract of finger millet showed antimicrobial activity against *Bacillus cereus* and *Aspergillus flavus* (Viswanath et al. 2009). Phenols in finger millet are responsible for reduction in fungal load on germinating grains (Siwela et al. 2010). A novel antimicrobial peptide isolated from foxtail millet and barnyard millet similar to that from finger millet has shown strong antifungal properties against four major phytopathogenic fungi, namely *Alternaria, Trichoderma, Botrytis* and *Fusarium*. Similarly, reports are available for antimicrobial effect of extracts from pearl millet, sorghum, foxtail millets but reports on barnyard millet extracts are not abundant. In a study seed extracts of barnyard millet alongwith certain other minor cereals were analysed for their antagonistic effect on *Rhizoctonia solani*, *Macrophomina phaseolina* and *Fusarium oxysporum.* Results indicated a 23 kDa thaumatin like protein (TLP) to be responsible for the effect (Radhajeyalakshmi et al. 2003). An antimicrobial peptide described as EcAMP1 isolated from *Echinochloa crusgalli* seeds showed strong suppression of various phytopathogenic fungi including *Alternaria* and *Fusarium* sp. (Nolde et al. 2011). In another report, chloroform extract of *Echinochloa colona* showed antifungal activity against *Aspergillus oryzae* and *Aspergillus* niger. Whereas petroleum ether and methanolic extract of the same plant showed antagonistic effect on pathogenic gram positive and negative bacteria viz., *Streptococcus pneumonia*e, *Staphylococcus aureus*, *Escherichia coli,* and *Pseudomonas aeruginosa*. Results suggested *E. colona* to be a good source of antimicrobial compounds (Ajaib and Khan 2013). In a study conducted by Odintsova et al. (2008) two defensin compounds were isolated from *E. crusgalli* seeds that were reported to be antagonistic to *Phytophthora infestans* and other phytopathogens at low concentrations. Thus potential antimicrobial effects of barnyard millet extracts needs to be evaluated against variety of pathogens effecting plant as animal health. Phenolic compounds and other bioactive components in different fractions of barnyard millet needs to be analyzed for its future use in therapeutics and food preservatives. Research needs to be focused on activity of barnyard millet extracts for antimicrobial effect on pathogens as well as their bioactivity in human and animal model systems. Even endophytes and rhizospheric microbial community of this crop needs to be mined for stress tolerant and plant growth promoting microbes.

Stress tolerance in barnyard millet

Plants follow sessile pattern of living and thus face plethora of biotic and abiotic stress conditions in nature. For adaptation under stressed conditions, plants undergo alterations at cellular, molecular, and physiological level and this is followed by reduced productivity in plant. Stress tolerance demands physiological cost (Bray et al. 2000). Phenological and biochemical adjustment of the plants to these challenging conditions is one of the most important traits to ensure climate resilient agriculture and promise food security of the nation. Their potential for climate resilient agriculture is still underexploited. Millets are C4 plants with better water and nitrogen use efficiency that are well adopted to drought, hot, arid and semiarid conditions, these are known to cope up with biotic and abiotic stress conditions (Dwivedi et al. 2012). There is a need to enhance crop diversification and maintaining sustainable agriculture to cope up with biotic and abiotic stress conditions and upcoming threats in the environment. There is a need to find alternatives, and thus exploring untapped diversity of cultivable plants adapted to various agro-ecological conditions. (Toledo and Burlingame 2006; Burke et al. 2009). Isolated farming communities often cultivate dozens of locally known millet landraces that are valued for a wide variety of traits (e.g., short duration to combat delayed rains as the result of climate change). They can withstand a certain degree of severe environmental pressures like soil acidity and alkalinity, stress due to moisture and temperature, drought, flood, and variation in soils from heavy to sandy infertile (Michaelraj and Shanmugam 2013; Gupta et al. 2010; Dhanalakshmi et al. 2019). It can also survive in presence of heavy metals, thus there are reports of barnyard millet being used in reclamation of soils contaminated with arsenic and cadmium (Sherif 2007; Abe et al. 2011). Barnyard millet and other minor cereals are reported to show resistance to pests and diseases (Devi et al. 2014). These are traditional crops of hilly areas that are constantly exposed to erratic rainfall, hailstorm, drought and temperature fluctuations and varying photoperiods. These climate resilient crops are well adapted to different agro-ecological niches and thus can survive harsh conditions of hill agriculture where other crop options are limited. Plants exposure to stress leads to accumulation of reactive oxygen species (ROS) in cells. Thus abundance of enzymatic and non- enzymatic ROS scavengers is a remarkable characterstic of plants that are better adapted to stressed conditions and thus can be used as a screening feature for selection of stress tolerance plants. In accordance with a study conducted by Trivedi et al. (2017) enoromous variability was recorded in antioxidant pool and antioxidative enzymes in various barnyard millet genotypes in Central Himalayan region for abiotic stress tolerance. Alteration in antioxidants (enzymatic and non-enzymatic) thus may be one of the reasons for stress adaptation in barnyard millet that produce sufficient harvest and substantial economic yield under hash and marginal conditions. Barnyard millet can even grow under limiting nitrogen conditions (Goron and Raizada 2015). It is known for its high degree of tolerance to salinity and their wild counterparts are highly suitable for cultivation in salt affected areas as fodder crops (Arthi et al. 2019; Al Sherif 2007). Because of its deep root system it can efficiently utilize available moisture and remains an important crop for subsistence farming by small farmers. Barnyard millet is a drought resistant crop and can withstand waterlogging conditions as well. Being C4 plant it can bypass photorespiration and thus can efficiently survive under low moisture conditions in arid and semi arid regions. Indian barnyard millet contains antifeedants which are present at concentrations higher than in rice, and it displays resistance to the feeding activity of pests like brown planthopper (Kim et al. 2008). Many reports also exist regarding their high degree of pest resistance and long-term storability, both traits which make the cultivation of barnyard millet and other millets a good insurance against famine and crop failure (Tsehaye et al. 2006; Reddy et al. 2011).

Constraints in barnyard millet cultivation

In India, barnyard millet cultivation is limited to certain aforementioned states. Yield level of this crop here is 1.5–2 t/ha whereas in Japan it is 10 t/ha, this huge difference indicate the scope for exploiting its potential in India. Cultivation and diversity of barnyard millet along with other minor cereals has been declining over periods in India. There are evidences in the literature to indicate that diversity in barnyard millet is fast eroding. In a report from 11 villages in Garhwal Himalayas where this crop is extensively grown, area under cultivation has been reduced by 72% (Maikhuri et al. 2001). However, certain organizations have come forward and germplasm collection programmes has been done by Vivekanand Parvatiya Krishi Anusandhan (VPKAS), National Bureau of plant genetic resources (NBPGR) and various other organizations (Gupta et al. 2009). The decline in cultivation of barnyard and other small millets in India can be attributed to various agronomic, economic, and social factors. The "Green Revolution" in 1970 brought a major change in agriculture by promoting the cultivation of major staple crops such as rice, maize and wheat. High yielding varieties were introduced which were successful in saving people from starvation, for instance, IR8 variety of rice was used in Punjab during famine period, this semi dwarf variety yielded ten times better than wild type (Evenson and Golin 2003). All this pushed small millets into even more marginal areas and were regarded as crops for poor. Agricultural policies focusing on mainstream cereals have pushed these millets aside in several countries. For instance, maize cultivation is preferred over finger millet in Kenya (Dida et al. 2008). Similarly, in Japan cold tolerant varieties of rice are cultivated instead of traditional barnyard millet (Yabuno 1987). Constant negligence and avoidance lead to loss of genetic diversity and preserved overall knowledge about these crops which caused inefficient production. Genetic studies and resources for this crop is meager. Lack of high yielding varieties, poor seeds and unimproved cultivation practices with poor technological advancements compounded by poorly organized integration with market makes their worldwide acceptance challenging. Various socioeconomic factors have contributed to decline in millet cultivation, these crops are labor intensive and till now mostly post harvest processing of the crop is performed manually by local women (Rengalakshmi 2005). Lag in increased yield of millets is majorly due to poor quality seed stocks, outdated cultivation practices and insufficient technological advancement specifically dedicated to millet cultivation that offer ample room for improvement (Padulosi et al. 2015). Besides these factors some amount of yield loss can be attributed to diseases that infect this crop like banded leaf and sheath bight, grain smut etc. (Pall et al.1980; Kumar and Prasad 2009; Kumar 2013). Table 2 represents some of the diseases affecting barnyard millet but majority of them cause minor crop losses. Major biotic constraint in Barnyard millet production in countries like India, Japan and China is due to *Ustilagopanici-frumentacei. E. esculenta* accessions are mostly resistant towards grain smut in comparison to *E. frumentacea* (Sood et al. 2020).

Most of the genotypes of banyard millet produce non-glutinous seeds thus resulting in poor texture of the food products and in most of the countries waxy textured grains such as rice are preferred. Thus for making it more attractive improved texture is required that can be achieved via suitable breeding practices (Sood et al. 2020). Another challenge effecting millet cultivation is lower yield of millets (Plaza-Wuthrich and Tadele 2012). All the public and private investments, agricultural research and development policies are mainly emphasized on increasing production of the three main staple crops viz., rice, wheat and maize

Table 2 List of major diseases in barnyard millet and their causative agents

Disease	Causative agent	References
Grain smut	*Ustilago-panici frumentacei* Bref	Kumar (2013)
Leaf blight	*Exserohilum monoceras*	Sood et al. (2020)
Head smut	*Ustilago crusgalli*	Kulkarni (1922)
Kernel smut	*Ustilago paradoxa*	Viswanath et al. (1989)
Leaf spot	*Helminthosporium crusgalli, Cercospora fujimaculans*	Drechsler (1923) and Sood et al. (2020)
Anthracnose	*Colletotrichum echinochloe*	Sood et al. (2020)
Banded sheath blight	*Rhizoctonia solani*	Kumar and Prasad (2009)

whilst investment in other crops still remains low (Pingali 2015). Farmers obtain lower returns on millet cultivation as compared to other cash crops, thus poor economic performance holds one of the reasons for their negligence. Seed availability and distribution that is limited to rural seed systems also effects millet productivity (Nagrajan and Smale 2007). Industrial methods for millet processing are not as well developed as wheat and rice (Saleh et al. 2013). Besides, lack of awareness, inadequate support from policy makers and limited investment for research and development of small millets are some of the major obstacles that require integrated strategies like crop diversification and increasing research investment towards these underutilized crops. Currently, all the considerable policies and research programs are focused on major cereals such as wheat and rice. Redirecting some portion of the allocated funds towards small millets can provide nutritional benefit along with a better production even under existing challenging conditions that might affect major cereal production (Padulosi et al. 2009, 2015).

Research so far on barnyard millet

Studies so far on barnyard millet has been confined to traditional practices of morphological, biochemical and cytological characterization of its germplasm. To date data regarding collection, preservation, and conservation of its germplasm is restricted (Mehta et al.2005; Gupta et al. 2009; Trivedi et al. 2017). Study based on performance of barnyard millet and changes in morphological and agronomic traits under stressed conditions have also been conducted (Dhanalakshmi et al. 2019). Multivariate methods has been used for analyizing morphological variations in germplasm collection (Gupta et al. 2009). Genetic enhancement of barnyard millet was performed by hybridizing two domesticated species i.e. *E. frumentacea* and *E. esculenta* for introgession of desirable traits (Sood et al. 2014). Studies based on path coefficient analysis have been conducted to determine the interrelationships among yield and related characteristics in barnyard millet for developing selection criteria for improved grain yield (Dewey and Lu 1959; Kozak and Azevedo 2014). Sood et al. (2015) suggested certain traits like thick culms, number of racemes, longer inflorescence, taller plants, longer flag leaves along with optimum number of tillers per plant as an indirect selection criteria to select genotypes with higher yield. Different landraces of barnyard millet for agro morphological and disease resistance traits were characterized by Joshi et al.(2015).

Few studies based on exploiting their genetic diversity using molecular markers, such as randomly amplified polymorphic DNA (RAPD), simple sequence repeats (SSR), inter simple sequence repeats (ISSR), and single nucleotide polymorphism (SNP) are also scattered in literature (Altop and Mennan 2011; Prabha et al.2012; Dvorakova et al. 2015; Nozawa et al. 2006). Wallace et al. (2015) identified 10,816 SNPs across 65 accessions of *E. colona* and 8217 SNPs across 22 accessions of *E. crusgalli*. In a study, genetic diversity among different genotypes of barnyard millet was assessed using morphological and nutritional traits in combination with expressed sequence tag-simple sequence repeats (EST-SSR) markers (Manimekalai et al. 2018). Out of all the available molecular markers, SSR are most informative and desirable, these are codominant and can decode allelic diversity in eukaryotes (Mohan et al. 1997). Wallace and coworkers, characterized core collection of barnyard millet germplasm using whole genome typing by sequencing method (Wallace et al. 2015). Studies have been conducted regarding improvement of its silage quality via anaerobic fermentation (Srigopalram et al. 2018). Similarly, ethanopharmacological studies based on antioxidative and antimicrobial properties of *Echinochloa* sp. have been carried out (Ajaib and Khan 2013). Very limited crop improvement studies have been carried out in Barnyard millet. Only in recent years a successful variety PRJ-1 has been released for this crop (Yadav et al. 2010). Yadav and Yadav (2013) conducted an experiment to investigate performance of Japanese and Indian barnyard millet under varied conditions of fertility and concluded that Japanese Barnyard millet varieties performed better and are highly recommended for cultivation as a multipurpose crop in hilly areas of Uttarakhand. An investigation was carried out on barnyard millet (*Echinochloa* spp.) global germplasm collection to investigate the association among yield components and their direct and indirect effects on the grain yield of barnyard millet (Sood et al. 2016). Besides these, studies directed for phytoremediation of heavy metals like cadmium using barnyard millet are also available (Abe et al. 2011). Though this crop have advantageous traits over wheat, rice and maize, the genome based studies on these crop is very less and this can be validated from the fact that in this era of next generation sequencing there are few nucleotide sequences of barnyard millet in NCBI database in comparison to other cereals whose genome sequences are also present in the database (Babu et al. 2018). Only few reports are available on germplasm collection and conservation of barnyard millet. Germplasm of barnyard millet is available at national and international levels, which is a primary requirement for improvement of such crops as it allows it to be accessed by breeders and scientific groups for seeking advantageous agronomic, nutritional and stress resistance traits. However a very limited data is available for barnyard millet regarding transformation and transgenic development. There is only one report available for transformation study in barnyard millet (Gupta et al. 2001). This frequency needs to be accelerated in the plant and development of transformation protocols in planta for studying gene function by loss and gain of function of the respective gene thus shortening the time it usually takes in tissue culture and somaclonal variations. High variability exist in agro-morphological traits among different Indian barnyard millet genotypes. However, codominant satellites and SNPs are rare in this crop (Nozawa et al. 2006; Wallace et al. 2015).

Germplasm conservation and breeding objectives

Ex-situ conservation approaches are primarily used for conservation of millet genetic resources. Globally, around 8000 accessions of barnyard millet have been conserved till date and efforts are being made to release improved varieties with wider adaptation (Sood et al. 2020). For plant breeders, germplasm collection, characterization, long term and short term storage, conservation and revival are very important.

Characterization of Barnyard millet on phenotypic basis indicates that it has a highly diverse germplasm with various agronomic and nutritional traits. Major gene banks across the world where barnyard millet germplasm is conserved include Department of genetic resources I, National Institute of Agrobiological sciences in Japan where in total 3671 germplasm accessions are available for cultivated as well as wild type species, Institute of crop science, Chinese Academy of Agricultural Sciences in China, where 717 germplasm accessions are available. 306 germplasm accessions are available in National Centre for genetic resources conservation (Fort Collins, Colorado), USA (Sood et al. 2020). A collection of 2365 barnyard millet accessions is maintained at Consultative Group on International Agricultural Research. Similarly, International Crops Research Institute for the Semi Arid Tropics (ICRISAT) contains 743 active and 487 base collections. The National Centre for Genetic Resources Conservation, Colorado maintains 306 accessions from 33 countries. In India, National Bureau of Plant Genetic Resources (NBPGR) has 1718 accessions while All India coordinated small millets improvement project has 985 accessions (Upadhyaya et al. 2008; Sood et al. 2015).

However data regarding genetic map and sequencing studies is scarce for the genus *Echinochloa* (Dwiwedi et al. 2012; Upadhyay et al. 2014). ICRISAT recently developed a core collection of barnyard millet that in all contain 89 accessions for its domesticated species. All the members of the genus are polyploid and both domesticated species are hexaploids, with $2n=6x=54$ (where, $x=9$) and its genome size has been roughly estimated to be 1.44 gigabases using flow cytometry (Upadhyaya et al. 2008; Wallace et al. 2015).

Barnyard millet is still not a part of modern agriculture and thus breeding objectives also differ for it in comparison to the major cereals. Breeders prefer traits like easy dehulling and reduced plant height for developing new varities (Sood et al. 2020). Easy dehulling trait is useful for post harvest processing. One such genotype is genotype B 29, it is maintained at Indian Council of Agricultural research-Vivekanand Parvatiya Krishi Anusandhan Sansthan (VPKAS), Almora which is used for breeding practices (Gupta et al. 2015). Other preferable breeding traits include disease resistance, yield and grain quality (Sood et al. 2015). Besides, breeding targets also include efforts in improving qualitative traits such as protein content, texture, micronutrient content, and puffing quality etc. (Sood et al. 2015).

Hybridization is in Barnyard millet is tedious due to the presence of small florets which are difficult to emasculate thus most of the breeding programs are based on traditional practices such as mass and pure line selection (Gupta et al. 2006). Modern breeding approaches, such as induced mutagenesis has been effectively used for developing new varieties of small millets. For instance, gamma irradiation of a landrace, Nogehie resulted in waxy stable mutant lines (Hoshino et al.2010). Similarly in Japan, Chojuromochi, a glutinous cultivar was developed using similar approach (Sood et al. 2020). Interspecific hybridization has also been practiced for developing segregants with high yielding and early maturing traits (Mehta et al. 2005). The constraint in success of interspecific hybrids of distant gene pools is the incompatibility and fertility barrier (Sood et al. 2020). *E. esculenta* is more diverse in terms of morphological as well as agronomic traits in comparison to *E. frumentacea.* Thus intraspecific hybridization among *E.esculenta* genotypes can prove to be successful in maximizing the yield and other agro-morphological and economic traits (Sood et al. 2020). Due to the lack of genome sequence information, poor genetic resources and well saturated genetic maps, genomics assisted breeding is not so successful in Barnyard millet. Genome wide markers used in characterization studies in the plant are also traditional and non-reproducible (Altop and Mennan 2011). To date, no genetic maps have been reported in barnyard millet due to limited breeding efforts as well as lack of multiparental as well as biparental mapping populations (Sood et al. 2020).

Efforts required to save the future of the crop

Investment for development of superior varieties of barnyard and their processing is needed to increase their adoption and consumption globally. There is a need to screen trait specific germplasm and use it for crop improvement and cultivation in other such agro-ecological areas. Improvement can be done on existing cultivation practices, optimized seeding, providing technical support, conducting systematic studies on enhancing its productivity, investment on research and development, improving policies and communicating the dietary benefits to the targeted consumers regarding neglected and underutilized crops like barnyard millet for climate resilient agriculture along with nutritional and economic security of the country. Improved seeds should be provided to farmers at low rate, agronomic research and low cost technology within reach of poor farmers. Millets need to be integrated into the existing Public Distribution System along with several government schemes. Increased use of barnyard millets in various ready-to-eat value added food products such as baby food, snacks, nutrition powder, flour should be encouraged as it enhances their value in the market (Liu et al. 2012). Processing of barnyard millet till date is done manually by poor farmers and women in rural communities, there is a need for appropriate processing technologies for decortications and milling (Saleh et al. 2013). Well processed grains can help barnyard millet to find place in diets of non-traditional millet using population as well (Mal et al. 2010). Advancement in molecular techniques has lead to the development of stress tolerant, high yielding varieties of staple crops but progress for barnyard millet is limited. NGS technologies, high-throughput platforms and omics strategies can be used to mine the germplasm of this under researched crop for plausible complex traits that may help in crop improvement. Besides, transgenic varieties of barnyard millet can also be produced by expressing additional agronomic traits and thus make it to grab its position in common food basket. For crop improvement, traditional knowledge combined with molecular techniques can help to characterize these crops as these are reservoirs of valuable traits. Improvement needs to be done for improving seed banks and core collections for millets (Goron and Raizada 2015). Various molecular markers like AFLPs, RFLPs, ESTs, SSRs and other specific stress related biomarkers are still lacking for small millets (Dwivedi et al. 2012).

More research efforts in germplasm collecting, conserving, evaluating and utilizing, and developing high yielding cultivars, processing and utilization technologies and policy innervations are required to promote its cultivation and for food and nutritional security of vulnerable population under climate change scenario for sustainable agriculture. Within same plant family, there are conserved regions and these syntenic regions can be used to identify important trait specific alleles in barnyard millet by using comparative genomics. Standardization of protocols is needed for production and culturing of transgenic varieties of barnyard millet as certain reports are available for kodo, foxtail, and pearl millet (Kothari et al. 2005). Transformation studies are required to be conducted for this crop to develop disease resistant and stress tolerant varieties. Being rich source of nutrition, it can prove to be a functional food ingredient in daily lives of people. However more studies are required to be conducted regarding metabolism and bioactivity of its grains on human health. For successful genomic assisted breeding programs a well assembled reference genome sequence of the plant is required as there is no genome sequence information on barnyard millet (Sood et al. 2020). Figure 3 summarizes the efforts required to promote barnyard millet cultivation and nationwide acceptance. There is a need for systematic analysis of different genotypes for breeding and crop improvement and a collective effort from public, government and research community is required to save the future of this crop.

Conclusion

From the literature reviewed above, it can be concluded that barnyard millet would be a better choice over major staples for combating the problem of malnutrition, hunger and feeding the burgeoning population. Unlike rice and wheat that require high agricultural inputs, it grows well in dry regions as rain-fed crops and require lower input. Under prevailing conditions of climate change, global warming, water scarcity it can easily thrive and grow well in marginal soils. In addition to these agronomic advantages, barnyard millet can offer other benefits in ecological, nutritional, and socioeconomic areas and can prove to be a more resilient and accessible food system. Directing research practices towards its production and processing can not only help to improve nutritional security of poor people in rural and urban areas but can also have

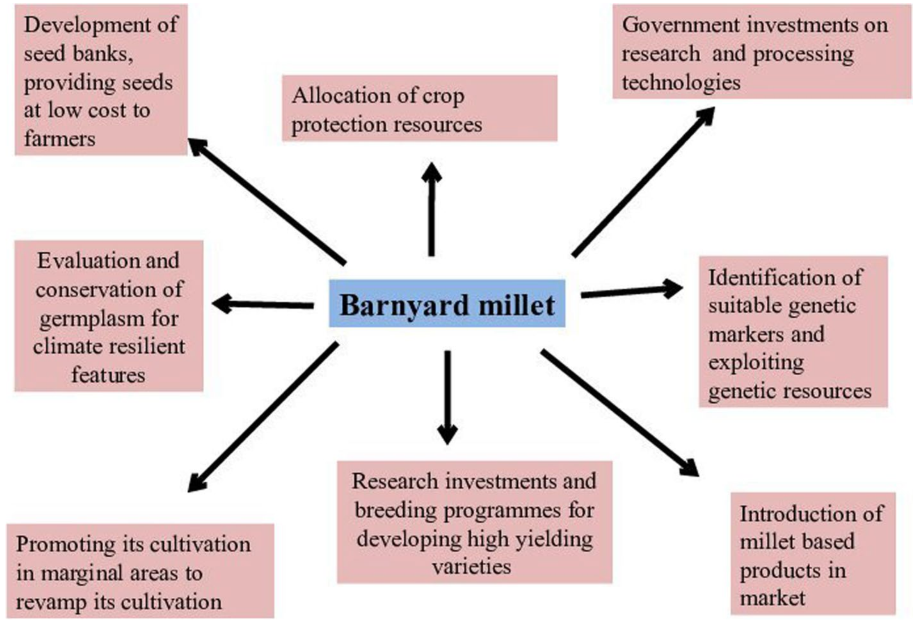

Fig. 3 Steps required to promote barnyard millet acceptance for agriculture and food security

strong social impact worldwide. To eradicate the problem of malnutrition that is threatening nutritional security, efforts need to be made towards these poorly addressed nutritious crops. Enhancing research and development of these minor neglected and underutilized crops can generate opportunities in providing income as well. These provide an increased productivity in low performing areas and may thus help reducing the yield gaps, and overall improved livelihood of vulnerable groups of community to achieve food sovereignty. Despite these valuable qualities its cultivation is still limited to poor farmers, thus an effort is needed to be made for encouraging local farmers to promote regional crops and stop forcing cultivation of wheat, rice and maize everywhere that require high additional inputs. Its ability to tolerate stress and robustness to grow in marginal lands makes it an excellent choice for exploring its potential and mining its genome for agronomically and nutritionally unique traits. Although, prospects of barnyard millet to be used as a major feed crop is limited but it may prove to be an important niche crop in drylands, high altitude regions with adverse climatic conditions.

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Declarations

Conflict of interest Authors declare that there is no conflict of interest.

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