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Proso millet (*Panicum miliaceum* L.)-a climate resilient crop for food and nutritional security: A Review

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Abstract

Proso millet (*Panicum miliaceum* L.) is an important short duration crop that adapts well to varied climatic conditions and is grown worldwide for food, feed and fodder purposes. Due to its lowest water and nutrient requirement, it has the potential for agriculture diversification. Nutritionally, proso millet grains are rich in proteins, vitamins, minerals, and micronutrients compared to other staple cereals. Recently the demand of the crop has increased due to its highly nutritious grains. Thus it has the potential to provide both food and nutritional security. Despite enormous potential, the crop has not gained the popularity among masses and is still considered as poor man's food. This work therefore is an attempt to compile the merge information available on crop history, phylogeny, germplasm resources, and present status to make the crop comprehensive and revamp its cultivation.

Key Words: ***domestication, germplasm resources, nutritional value, phylogeny, proso millet.***

Introduction

Small millets, including finger millet (*Eleusine coracana* (L.)Gaertn.), foxtail millet (*Setaria italica* (L.)P. Beauv.), proso millet (*Panicum miliaceum* L.), kodo millet (*Paspalum scrobiculatum* L.), little millet (*Panicum sumatrense* Roth. ex. Roem. &Schult.), and barnyard millet (*Echinochloa crus-galli* (L.) P. Beauv. And *E. colona* (L. Link) are well adapted to diverse climatic conditions and play an important role in food and nutritional security in rural households in regions where these crops are grown. Proso millet is one of the important small millets, commonly known as broomcorn millet, common millet, hog millet, Russian millet, and by other names in different regions. Vavilov (1926) suggested China as the center of diversity of proso millet, while Harlan (1975) suggested that proso millet was probably domesticated in China and Europe. Proso millet grows at a wide range of altitudes, with a short growth cycle of 6 to 12 weeks, and requires little water for growth and development. Proso millet is grown in northern China, Mongolia, Republic of Korea, southeastern Russia, Afghanistan, Pakistan, India, and southern Europe. The cultivation area of proso millet is 0.82 m ha in Russia, 0.7 to 1.0 m ha in China (Wang *et al*., 2016), 0.5 m ha in India (Salini *et al*., 2010) and 0.20 m ha in USA (Habiyaramye *et al*., 2017) however, the area in proso millet cultivation is declining owing to a shift of cultivation of major crops that give much higher yields and profit. Among the millet species produced worldwide, proso millet is the most important species traded in the world market. In the United States of America (USA) the focused breeding programme for proso millet productivity improvement was started in the year 1972 under the alternative crops breeding programme at Panhandle Research and Extension Centre (PHREC), and released several cultivars. In the United States of America (USA) there are 15 cultivars of proso millet available to growers, and nine of these were selections from adapted land races, and six were developed through hybridization followed selection (Habiyaramye *et al*., 2017). In India proso millet is largely grown in Madhya Pradesh, Eastern Uttar Pradesh, Bihar, Tamil Nadu, Maharashtra, Andhra Pradesh and Karnataka. In India it is cultivated over an area of 0.41 lakh ha with total production of about 0.22 lakh tones and with productivity of 531 kg/ha during the year 2015-16. Proso millet is used for feeding birds and as livestock feed in developed countries and for food in some parts of Asia (Rajput *et al*., 2014). In the USA, most of the proso millet

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crop is used for birdfeed and in cattle-fattening rations (Habiyaramye *et al*., 2017). Nutritionally, proso millet grains are rich in proteins, vitamins, minerals, and micronutrients including iron, zinc, copper and manganese, compared to other staple cereals (Gomeshe, 2017). Green plants are excellent fodder for cattle and horses and are also used as hay. Proso millet has been receiving growing interest from food industries in Europe and North America because of its mild flavor, light colour, gluten-free quality, and potential health benefits (Wang *et al*., 2016).India is the leading producer and consumer of millet crops and their products. The total area of small millets in India is around 1.63 m ha, with a production of 1.82 m tones during the year 2016-17 (Annual progress report 2018-19, ICAR-AICRP on small millets). The state-wise area, production and productivity of small millets in India are given in Table 1 and the top 5 countries in terms of production of small millets are given in Table 2.

History, Origin and Domestication

The genus *Panicum* is one of the largest genera of the grasses, including more than 400 species distributed primarily in the tropics and sub tropics and also warmer parts of temperate zones (Roshevits 1980). Within this large genus, two species are of economic importance; Proso millet (*Panicum miliaceum* L.) and Little millet (*Panicum sumatrense* Roth. ex. Roem. &Schult.). The genus *Panicum* is poorly represented in drier tropics, apart from a few more or less xerophytes species (Cobley 1976).Proso millet, an ancient Slav name used in Russia and Poland (Candolle, 1964), has also been called common millet, hog millet, broom corn, yellow hog, Hershey and white millet. Although the origin of proso millet has not been ascertained, it is one of the first cultivated cereal grasses, most likely prior to wheat. According to Matz (1986), however proso millet is probably a native of Egypt and Arabia and has been cultivated in Asia Minor and southern Europe since prehistoric times. Candolle (1964) also states that Egypt-Arabian origin of proso millet is very probable. Proso millet was likely domesticated in China sometime around 10,000 BP. Current archeological theorists believe that proso millet domestication took place around the beginning of the Holocene as global temperatures became warmer and hunter gatherers were exposed to new plants and environments (Bettinger *et al*. 2007, 2010b). Although archeologists have yet to agree on the exact timing of millet domestication, they generally agree that domestication likely took place separately in three different centers: (1) Northwest China (Bettinger*et al*., 2007, 2010b), (2) Central China (Lu *et al*., 2009), and (3) Inner Mongolia (Zhao, 2005). From these centers of domestication, millet spread widely throughout East Asia, including high-altitude areas such as the Tibetan Plateau. By the end of 2nd millennium BP, the cultivation of proso millet had spread to the rest of Central Eurasia and to Eastern Europe (Miller *et al*., 2016). Evidence shows major shifts in proso millet farming on the Tibetan Plateau until its cultivation was abandoned in Eastern Tibet (Guedes*et al*., 2014, 2015 a; Chen *et al*., 2015). Later proso millet was largely replaced by wheat and barley on the Tibetan Plateau; however, it continued to be a popular crop in low lying plains of northern China well after its introduction (Boivin *et al*., 2012). In Africa and India, it has been used as a staple food for thousands of years. In China, it was the prevalent grain before rice became the dominant staple (Bohle *et al*., 2003). In the 17th century, proso millet was first introduced to Canada. Unfortunately, wild proso millet has become one of the most aggressive grass weeds in North America since the early 1970. Proso millet expanded across Eurasia and was introduced to North America in the 1700s where it is now primarily used for animal fodder and bird seed (Bagdi *et al*., 2011).

Phylogeny

According to cytological investigators, proso millet is an allotetraploid cereal (2n=4x=36). Its genome progenitors are not clear, although phylogenetic data suggest *P. capillare* L. or a close relative as the maternal ancestor, with the other genome shared with *P. repens* L. (Hunt *et al*., 2014). It has been reported that the variation among these proso millet accessions is low when studied by isozyme and microsatellite molecular markers which likely reflect the double bottleneck of polyploidation and domestication (Hu *et al*. 2009; Hunt *et al*., 2011). A wild ancestor for proso millet has yet to be identified (Miller *et al*., 2016); however, weedy forms of millet, which may include a wild progenitor, are found across Eurasia (Zohary *et al*., 2012). Phylogenetic analysis revealed two sets of homologous chromosomes that may have merged ~5.6 million years ago, both of which exhibit

Table 1.Area, production and productivity of small millets in prominent states of India (2016-17)

States/UTs	Finger millet			Other small millets		
	Area	Production	Productivity	Area	Production	Productivity
	(In ' 000 Hectare)	(In ' 000 Tone)	(In Kg./Hectare)	(In ' 000 Hectare)	(In ' 000 Tone)	(In Kg./Hectare)
Andhra Pradesh	32.00	35.00	1094	31.00	24.00	774
Bihar	4.78	3.46	723	3.20	3.10	967
Chhattisgarh	6.30	1.50	238	89.20	25.40	285
Dadra and Nagar Haveli	0.86	1.46	1700	0.00	0.00	0.00
Goa	0.00	0.00	0.00	-	-	-
Gujarat	19.00	27.00	1421	22.00	28.00	1273
Himachal Pradesh	2.23	2.12	952	4.91	3.83	780
Jammu and Kashmir	8.30	3.60	434	9.10	3.76	413
Jharkhand	22.69	20.03	882	-		
Karnataka	598.00	858.97	1436	21.00	7.00	333
Kerala	0.03	0.04	1273	0.01	0.01	667
Madhya Pradesh	2.60	0.90	346	184.00	113.02	614
Maharashtra	92.70	111.10	1198	83.70	44.73	534
Nagaland	0.33	0.32	970	1.03	11.13	1110
Odisha	46.97	33.13	705	27.41	13.84	505
Puducherry	0.05	0.07	1426	0.00	0.01	1250
Sikkim	0.00	0.00	0.00	6.65	6.71	1009
Meghalaya	-	-	-	2.94	2.81	956
Tamil Nadu	61.36	114.43	1865	23.55	21.22	901
Telangana	1.00	1.00	1000	1.00	1.00	1000
Uttar Pradesh	-	-	-	9.00	5.00	556
Uttarakhand	107.00	160.00	1495	63.00	85.00	1349
West Bengal	9.91	10.99	1108	2.35	1.94	827
Arunachal Pradesh	-	-	-	5.28	27.03	5118
Rajasthan	-	-	-	14.67	10.19	695
Assam	-	-	-	4.75	2.93	616
India	**1016.11**	**1385.11**	**1363**	**619.11**	**441.94**	**714**

strong synteny with other grass species. Broomcorn millet contains 55,930 protein- coding genes and 339 microRNA genes. Paniceae-specific expansion in several subfamilies of the BTB (broad complex/tramtrack/bric-a-brac) subunit of ubiquitin E3 ligases, suggesting enhanced regulation of protein dynamics may have contributed to the evolution of broomcorn millet (Changsong *et al.,* 2019).

Botanical description

Proso millet is a warm- season annual grass, most frequently grown as a late-seeded summer crop (Baltensperger, 2002) and can complete its life cycle within 60-100 days (Baltensperger, 2002).

Table 2. Top five small millet producers in the world, 2016.

Sl. No.	Country	Production (t)
1	India	10,280,000
2	Niger	3,886,079
3	Mali	1,806,559
4	Nigeria	1,552,576
5	Sudan	1,449,000

Source: FAOSTAT, 2016
(http://faostat3.fao.org/browse/Q/QC/E

A compact panicle droops at the top like an old broom, hence proso millets common name, “broom corn” (Changmei and Dorothy, 2014). Grains are round about 3mm long and 2mm wide, and enclosed in a smooth hull, which is typically white or creamy white, yellow, or red in colour, but may be gray, brown or black. White seeded varieties are most often grown in the U.S., followed by red seeded varieties (Baltensperger, 2002; Changmei and Dorothy 2014). Stems are light green, erect, sometimes branched at the base and grow 30 to 100 cm tall, with few tillers (Baltensperger, 2002). Proso millet stems and leaves are covered with slight hairs. The leaves may be up to 30 cm long with short ligules but no auricles. Plants have shallow, fibrous root systems and produce few tillers.

Proso millet inflorescence is a –drooping panicle, 10-45 cm long that may be open or compact primary branches spreading or ascending or oppressed, terminating in a spikelet. The bristles below the spikelets are absent. The spikelets are generally solitary and about 0.5 cm long (Gowda *et al.,* 2003). Each spikelet contains two glumes and two lemmas. The glumes are unequal in length; outer glume is short, while the inner glume is as long as the spikelet. Each lemma contains one floret. The floret in lower lemma is sterile without stamen; upper lemma is fertile and shorter than lower lemma. The palea of lower lemma (sterile floret) is very much reduced, while the palea of upper lemma (fertile floret) is well present (Seetharam *et al*., 2003). It has three stamens; anthers are tan or amber or blackish or dark brown in colour. The ovary has bifid style and plumose stigmas (Nanda and Agrawal, 2008).

Anthesis and pollination

Proso millet starts flowering from top to downward to the bottom of the panicle. The timing of anthesis in proso millet between 10.00 AM and 12 noons. It takes 12-15 days from start of the anthesis of the first flower to the last floret on the panicle. In proso millet the receptivity of stigma coincides with the shedding of pollen from anthers. Nelson (1984) observed that when the florets were open, the anthers were sticky and pollen did not shed. Within minutes after the opening of florets, the anthers dried out and begin to shed pollen. The florets remain open for 10-15 minutes. The factors such as high temperatures, low humidity and bright sunlight promote the flowering. Flowering gets reduced on cloudy days. It can be stimulated by heating panicles with lens. Proso millet (2n=36) is a self pollinated crop, but natural cross pollination may exceed 10%.

Growth and development

Growth and development characteristics of proso millet were explained in detail by Cardenas *et al*., (1983), they distinguished three phases; vegetative, reproductive, and ripening, which may be further subdivided into physiologically distinct stages. The vegetative phase covers the period from germination to panicle initiation, depending on the cultivar used and climate in the area may be completed 16 to 20 days after planting. An increase in number of leaves, tillers, and plant height are characteristics of this phase. The period, about 20 to 25 days, from panicle differentiation to flowering of main Culm in the reproduction phase. The phase initiates when the panicle primordial is greater than 0.5 mm. Rapid elongation of stem internodes and an increase in leaf area accompanied by more tillers are noticed in this phase. The ripening phase starts at flowering or blooming and continues to the end of physiological maturity, which covers a period of 20 to 30 days. Throughout this period, the plant actively accumulates dry matter, particularly in grains. The authors concluded that since proso accumulates higher dry matter in the reproductive parts compared to wheat, maize and sorghum, it may be advantageous to grow proso in dry and short growing seasons. Physiological maturity proceeds from top to bottom of the panicle. The ripening of the seed is not uniform throughout panicle and delay in harvesting may cause losses due to shattering (Baltensperger *et al*., 1995a).

Environmental requirement

Proso millet is highly drought- resistant, which makes it of interest to regions with low water availability and longer periods without rain. Proso millet also grows under non-irrigated conditions in arid lands with as little as 200-500 mm of average annual precipitation (Ceccarelli and Grando, 1996), and can produce grain with only 330-350 mm of annual rainfall (Lyon *et al*., 2008a). As a warm season crop, proso millet is sensitive to frost and requires warm temperatures for seed germination and development. Optimal soil temperatures for seed germination range from 20-30^{o} C (Amadou *et al*., 2013). Proso millet has very low transcription ratio, which may be attributed in part to the C4 photosynthetic mechanism. Proso millet avoids drought sensitivity by reaching maturity rapidly In addition, at temperatures above 30^{o} C, proso millet stops vegetative growth, ceases to flower, and maintains its primary stem at a shorter height to better resist drought conditions (Sateesh, 2010; Changmei and Dorothy, 2014). Proso millet can be grown on sandy loam, slightly acidic, saline and low fertility soils (Changmei and Dorothy 2014). However, this crop grows poorly on water logged soils (Seghatoteslami *et al*., 2008). Proso millet thrives in low pH soils and most of its seeds germinate well on soil pH of 5.5 to 6.5 (Lyon *et al*., 2008). However, plants grown on soils with pH above 7.8 show symptoms of iron chlorosis. Substantial salinity tolerance has been reported in proso millet but with significant varietal diversity with some especially tolerant varieties reported. A higher sodium concentration in roots compared to shoots has been suggested as a biomarker for future breeding efforts (Liu *et al*., 2014a; Sabir *et al*., 2011).

Germplasm resources

Germplasm resources provide pool of genes for breeding high-yielding, biotic and abiotic resistant cultivars. Systematic breeding efforts and utilization of genetic resources are limited in small millets. Use of germplasm accessions in breeding programme can be enhanced if small subsets of a few hundred germplasm lines, which represent the entire diversity of is available. Such germplasm representative subsets are available in small millets collection from ICRISAT. These diversity sets such as core and mini core collections could be effectively evaluated to identify germplasm trait-specific sources for their enhanced utilization in breeding high yielding cultivars with diverse adaptation. Conservation and increased use of proso millet germplasm, especially for breeding, new cultivars, requires information on its genetic diversity (Hu *et al* 2008; Dvorakova *et al*., 2015). Gene banks worldwide hold a rich collection of proso millet accessions, especially in areas where proso millet is still grown. The farmers grow and preserve land races of proso millet, often in remote areas of the world, thus maintaining its agricultural and functional diversity. The land races have helped agrarian communities survive for generations in marginal lands (Newmaster *et al*., 2013). Globally over 29,000 germplasm accessions of proso millets have been conserved in gene banks, with the major collections of proso millet germplasm accessions held in Russia, China, Ukraine, and India (Upadhyaya *et al*., 2015). The organizations manage Proso millet germplasm banks of their own, the largest of which are summarized in Table 3.In the ICRISAT gene bank, 849 accessions of proso millet are held, and a core collection (106 accessions) representing the entire collection has been established (Upadhyaya *et al*., 2011). The diversity of this collection has been characterized in terms of flowering time, plant height, panicle exertion, and inflorescence length (Reddy *et al.,* 2007). The largest collection of proso millet is held by the N.I. Vavilov All Russian Scientific Research Institute of Plant Industry in St. Petersburg, with roughly 8777 accessions as of 2012 (Dwivedi *et al*., 2012). A total of 611 proso millet germplasm have been collected, conserved and maintained at National Active Germplasm Site (NAGS), Project Coordinating Unit, Small millets, University of Agricultural Sciences, Bengaluru.

Genetic improvement

Genetic improvement and cultivar develop of proso millet, as in other small millets, has been achieved largely through direct selection of promising germplasm. In India, 24 cultivars have been released, of which seven were developed by hybridization followed by selection and the remaining by selection from landraces. Recentlyreleased varieties of proso millet in India (2005 to 2017) are given in Table 4. (http://www.aicrpsm.res.in/Releasevarieties.html).

Development of high yielding varieties in India

In the year 1960, high yielding varieties such as Ram Cheena and ShyamCheena has been released using pureline selection from Agricultural Research Station of Rajendra Prasad Agricultural University, Dholi, Bihar. GPUP 8 (1999) and GPUP 21 (2003), the high yielding varieties has been released from Project Coordinating Unit on Small millets, Bengaluru. Agricultural Research Station of TNAU also released varieties such as TNAU 143, TNAU 145, TNAU 151, TNAU 164 and TNAU 202 during 2007 to 2011. The variety TNAU 164 exhibits imperative traits viz, lodging resistance, resistance to shoot fly damage and rust disease. DHP 2769 the high yielding variety has been released recently from Agricultural Research Station, Hanumanamatti (http://www.aicrpsm.res.in/Releasevarieties.html).

Table 3. Significant germplasm collections of proso millet (Goron *et al*., 2015)

SN.	Institution	Headquarters	Number of accessions
1	N.I. Vavilov All Russian Scientific Research Institute of Plant Industry	St. Petersburg, Russian Federation	8778 (Dviwedi *et al*., 2012)
2	Institute of Crop Germplasm Resources, Chinese Academy of Agricultural Sciences (ICGR-CAAS)	Beijing, China	6517 (Dviwedi *et al.*, 2012)
3	Ustymivka Experimental Station of Plant Production	S. Ustymivka, Ukraine	3976 (Dviwedi *et al.*, 2012)
4	Yuryev Plant Production Institute UAAS	Kharkiv, Ukraine	1046 (Dviwedi *et al.*, 2012)
5	International Crops Research Institute for the Semi-Arid Tropics (ICRISAT)	Patancheru, India	849 (Upadhyaya *et al.* 2011).
6	Botanical Harden of the Plant Breeding and Acclimatization Institute	Bydgoszcz, Poland	721(Dviwedi *et al.*, 2012)
7	USDA Agricultural Research Service (USDA-ARS)	Griffin, USA	719(http://www.ars-gron.gov/npgs/index.html)
8	North Central Reg. Plant Introd. Station, (USDA-ARS)	Ames, USA	713 (Dviwedi *et al.*, 2012)
9	Estacion de lguala, Instituto Nacional de investgaciones Agricolas (INIA)	Iguala, Mexico	400 (Dviwedi *et al.*, 2012)
10	National Institute of Agrobiological Sciences (NIAS)	Kannondai, Japan	302 (http://www.gene.affrc.go.jp/index_en.php)
11	National Active Germplasm Site (NAGs)	Project Coordinating unit on Small millets, University of Agricultural Sciences, Bengaluru	611 (www.aicrpsm.res.in)

A total of 200 accessions of proso millet originating in 30 countries were evaluated in two rainy seasons to access phenotypic diversity for morpho-agronomic and grain nutritional traits and to identify high grain yielding and grain nutrient-rich accessions. Proso millet diversity was structured by geographical region, by country within region, and by racial group. Race *patentissimum*showed high diversity and *ovatum* low diversity, and diverged widely from each other. The lowest divergence was observed between races *compactum* and *ovatum*. Eighteen high grain yielding, 10 large seeded, and 26 two or more grain nutrients-rich accessions were identified, and highly diverse pairs of accessions within and between trait groups were identified (Vetriventhan and Upadhyaya, 2018).

Genomic resources

Genomic resources such as DNA markers, linkage maps, and genome sequence are essential for gene tagging, QTL (quantitative trait loci) mapping, and marker assisted selection for rapid crop improvement. The genetic sequence diversity of proso millet has been examined to a limited degree. The sequence diversity is moderate to high (Karam*et al*., 2006; Cho *et al*., 2010; Hunt *et al*, 2011), perhaps due to continuing hybridization with wild varieties (Colosi and Schaal, 1997). Preliminary diversity clustering based on agronomic traits was performed on the Chinese collection for the purpose of SSR based characterization (Hu *et al*., 2009) Several types of molecular markers have been used to estimate genetic diversity and relatedness in *Panicum miliaceum* accessions, including amplified fragment length polymorphism (AFLP) (Karam *et al*., 2004, 2006). Random amplified polymorphism DNA (RAPD) (M'Ribu and Hilu, 1994; Colosi and Schaal 1997). Cleaved amplified polymorphic DNA (CAP) (Lagler *et al*., 2005) and SSR markers (Hu *et al*., 2009; Cho *et al.,* 2010; Hunt *et al*, 2010, 2011; Rajput *et al*., 2014 Dvorakova *et al* 2015;

Table 4. Recently released varieties of proso millet in India (2005 to 2018)

SN	Name of variety	Pedigree	Institute where developed	Year of release	Maturity (days)	Avg. Yield (q/ha)	Area of adaptation	Special features
1	TNAU 145	PV 1454 x TNAU 96	TNAU, Coimbatore	2007	70-72	18-20	Tamil Nadu	High yielding, superior grain quality for value addition.
2	CO(PV) 5 (TNAU 143)	PV 1403 x GPUP 21	TNAU, Coimbatore	2007	70-75	23-25	National	High yield, profuse tillering, drought tolerant
3	TNAU 151	TNAU 96 x PV 1673	TNAU, Coimbatore	2008	72-75	18-20	National	Bold grains, tolerant to shootfly
4	TNAU 164	TNAU 137 x CO 4	TNAU, Coimbatore	2009	70-75	18-20	National	Non lodging, tolerant to shootfly and rust
5	Pratap Cheena-1 (PR-18)	Pureline selection	MPUA &T, Udaipur	2006	65-70	15-17	National	Early duration, dual purpose.
6	PRC 1	Selection from GPMS 519	Ranichauri, GBPUA&T, Pantnagar	2008	70-75	10-12	Uttarakhand hills	Resistant to leaf blight
7	TNAU 202	PV 1453 x GPUP 16	TNAU, Coimbatore	2011	70-75	18-20	National	Profuse tillering and bold grains
8	TNPm 230	TNAU 164 x IPM-19	TNAU, Coimbatore	2017	70-75	21-23	National	Short duration, drought tolerant variety
9	DHP-2769	Selection from IPM-2769	ARS, Hanumanamatti, UAS, Dharwad	2018	70-72	20-22	Agro-climatic zone-3 and Zone 8 of Karnataka state	Suitable for contingency planting

Table 5: Nutritional composition of proso millet (*Panicum miliaceum* L.) compared to other small millets, wheat and rice.

SN	Crop	Protein (g)	Carbohydrate (g)	Fat (g)	Dietary fiber (g)	Calcium (g)	Phosphorous (mg)	Fe (mg)
1	Proso millet (*Panicum miliaceum* L)	12.5	70.4	3.1	14.2	14	206	10.0
2	Finger millet (*Eleusine coracana* (L.) Gaertn.	7.3	72.0	1.3	18.8	344	283	3.9
3	Kodo millet (*Paspalum scrobiculatum* L.)	8.3	65.0	1.4	15.0	27	188	12.0
4	Foxtail millet (*Setaria italica* (L.) P.Beauv.	12.3	60.9	4.3	14.0	31	290	5.0
5	Little millet (*Panicum sumatrense* Roth ex Roem. And Schult.	7.7	67.0	4.7	12.2	17	220	6.0
6	Barnyard millet (*Echinochloa esculenta* (A. Braun)H. Scholz	6.2	65.5	2.2	13.7	11	280	15.0
7	Wheat (*Triticum aestivum* L.)	11.8	71.2	1.5	12.9	41	306	3.5
8	Rice (*Oryza sativa* L.)	6.8	78.2	0.5	5.2	45	160	1.8

Rajput and Santra, 2016). Colosi and Shaal (1997) found 97 RAPD genotypes (69 wild proso millet, 26 crop and feral crop weed, 2 hybrids between crop and wild types) among 398 individuals with DNA polymorphism suggesting hybridization between wild proso millet and crop biotypes in about 10% of the genotypes. Molecular markers in proso millet have often been derived from the available sequence data of related species including switch grass, rice, wheat, barley and oat (Hu *et al*., 2009; Rajput *et al*., 2014). AFLP markers have shown promise in grouping proso millet based on biotype, but were significant in differentiating between wild and cultivated varieties (Karam*et a*l., 2004).

Hu *et al*., (2009) used 46 SSR markers from rice, wheat, oat and barley to examine the genetic diversity of 118 Chinese accessions with different ecotypes. The genetic similarity (GS) coefficients among the accessions were moderate to high and Hu *et al*., (2009) grouped the accessions into five clusters which closely corresponded with the ecological areas of the collection sites. The clustering of accessions was also consistent with the GS matrix. Cho *et al*., (2010) developed the first SSR markers for proso millet by constructing a SSR-enriched library from genomic DNA. They tested 25 markers on 50 accessions of *P. miliaceum* and detected 110 alleles. Hunt *et al*., (2011) used 16 of the markers developed by Cho *et al*., (2010) to examine the genetic diversity and phylogeography of 98 land races accessions across Eurasia.

Liu *et al*., (2016) used high-throughput sequencing to develop SSR markers specific to proso millet and thus increase the number of SSR markers researchers can use. They generated 500 primer pairs which they screened on eight accessions randomly selected from pool of 73 Chinese accessions. Of these, 162 primer pairs produced polymorphic and reproducible fragments from these primer pairs, 67 SSR markers were developed and used to examine the genetic diversity of 88 accessions consisting of land races and cultivars. They detected 179 alleles and 349 genotypes, revealing a moderate level of genetic diversity. Rajput *and* Santra (2016) constructed the first genetic linkage map of proso millet using SNP markers discovered through genotype by sequencing (GBS), an application of next generation sequencing (NGS) protocols (Hu *et al*., 2014). A total of 833 SNPs were eventually used to construct the linkage map which has 18 linkage groups. Since this is the first genetic map for proso millet, each linkage group was considered a chromosome as the haploid genome of proso millet has 18 chromosome. Using these SNP markers, Rajput *and* Santra (2016) mapped 18 quantitative trait loci (QTL) for eight traits , namely lodging, heading date, plant height, peduncle length, panicle length, grain shattering, 1000 grain weight and grains per panicle. These QTLs accounted for medium to high phenotypic variance (13-35%). Using the Illumina high-throughput, paired-end RNA sequencing technology, Yue *et al*., (2016b) assembled and characterized de novo the proso millet transcriptome, the entire collection of RNA sequences in a cell. A broomcorn millet landrace originating from Northern China was selected for genome sequencing and assembly. The genome size was estimated to be ~923 Mb based on a K-mer analysis (Changsong *et al.,* 2019).

Nutritional and health benefits

Millets are a major source of energy and protein and have high nutritive value, comparable to major cereals such as wheat, and rice Nutritional composition of proso millet (*Panicum miliaceum* L.) compared to other small millets, wheat and rice (Amadou *et al*., 2013; Saleh *et al*., 2013) given in Table 5. The benefits of consuming proso millet include its high protein content which ranges from 11.3 to 17% of grain dry matter and its grains are richer in essential amino acids (leucine, isoleucine and methionine) than those of wheat (Kalinova and Moudry, 2006; Saleh *et al*., 2013). Genotypic diversity in protein content and amino acid profile has been observed (Kalinova and Moudry, 2006). The husked grain is nutritious and is eaten whole, boiled, or cooked like rice (*Oriza sativa* L.) Sometimes it is ground to make roti (flatbread). Starch is the main carbohydrate in the grain and is similar to corn starch; it is suitable as a sizing agent in the textile industry. Like other small millets, the applicability of the grain in preventing cancer, heart disease and managing liver disease and diabetes has been investigated with promising results (Nishizawa *et al*., 2002; Zhang *et al*., 2014; Srivastava *et al*., 2001; Shimanuki *et al*., 2006). There may be additional untapped phytochemical value as indicated by a wide range of genotype-specific grain colors (Zhang e*t al*., 2014). Proso millet is poor in calcium but the seeds contain a high amount of phosphorus. However the bond of phosphorous with phytates decreases considerably phosphorous availability. Proso millet is rich in potassium but also in iron and manganese (19.5-20.6 mg/100 g). Proso millet is good source of zinc (Demirbas 2005), copper and boron. Cereal grains are the most important source of dietary fiber in the human diet. Fiber content in the human diet plays an important role in prevention and treatment of high blood pressure and high levels of cholesterol (He *et al*., 2001). Fiber content in dehulled grains of proso millet is at a similar level to oat (0.8-1.2%); in the caryopsis it constitutes about 9.6% (Geervani and Eggum 1989a; Kalinova 2002). The soluble fiber reaches about 36% of total fiber. Proso millet accessions showed a wide range of variation for grain nutrient content: Fe, 41-73 mg kg-1,; Zn, 26-47 mg kg-1; Ca, 91-241 mg kg-1; protein, 11% - 19% (Vetriventhan and Upadhyaya ,2018).

Phenolic compounds

Polyphenols in cereals have an adverse influence on colour flavor, and nutritional quality. These compounds are mostly located in the outer layers of the grain. Factors such as plant part, stage of development, and environment content of phenolic compounds in proso millet is about 0.05-0.10 mg/100g of catechin equivalents dry basis (Dendy 1995). Polyphenols interact with proteins and create tannin-protein complexes. Dark coloured (black and brown) grains have higher tannin content than light grains. De hulling of grains reduces the level of tannin content to 65-80% because hulls contain 15-40 times more tannin as the dehulled grains (Lorenz 1983). Phytic acid content in proso millet ranges from 0.17 to 0.61g/100g and it is higher than in polished rice and lower than in wheat (Lorenz 1983). The percentage of total phosphorous present in the phytic acid form in proso millet is about 67.3%. Dehulling reduces the phytate content by 17-24%. Milling, soaking, cooking, fermentation and bread making can also reduce phytic acid content of food.

Future scope of work and prospects

Over the last few years, there has been increasing recognition of small millets nutrient composition and benefits as healthy food. Considering their diverse adaptation and agronomic and health benefits, small millets could be an alternate or supplementary crop to enlarge the food basket to ensure food, feed and nutritional security. Proso millet is one of the under- researched and underutilized small millets and a potential climate -smart and nutrient- rich crop. With its short growing season, proso millet can be planted late as a catch crop when main crops fail. Molecular markers based on coding and non-coding regions of the proso millet genome were developed and used in genetic diversity analysis of land races, breeding lines and cultivars. These molecular markers were also used on phylogenetic and phylogeographic studies to elucidate the genetic relationships of accessions and their geographical origins. In addition, molecular markers were used to trace the spread of proso millet from its center of domestication, identify its progenitor. However with the discovery of SNPs by GBS and identification of differentially expressed genes and thousands of SSR and SNP loci by transcriptome analysis, a considerable number of molecular markers are currently available of genomic research in proso millet. With the construction of the first genetic linkage map using SNP and the first QTL mapping study conducted in proso millet, there are now promising tools for molecular breeding of this crop. Even though there are some studies reported in the literature about the nutritional composition, health benefits and uses of proso millet, there is still a broad gap in the literature especially on the nutritional composition of different varieties and its applications in different food products. More research is required to breed millet cultivars suited to different agro ecosystems and to formulate best production practices. There is a need to correlate the agronomic characteristics with the nutritional properties and end use of proso millet.

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