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Nutritional Bio-fortification in Pearl Millet

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ABSTRACT

Research on millets and their food value is in its infancy and its potential is vastly untapped. This review focuses on nutritional enhancement and improvement in pearl millet (*Pennisetum glaucum* (L.) R. Br.), a staple food crop of the semi-arid tropics largely grown for food and fodder in sub-Saharan Africa and parts of India. Climate change will greatly affect what crops we grow and where we grow it. Two of the most comprehensive models of climate change suggest that pearl millet is among the winner crops which are likely to be most suited and widely cultivated in future. Pearl millet is mainly grown for grain but it is also valued for its stove and/or forage. Apart from being used as food for human consumption and feed for livestock and poultry, pearl millet grain is also gaining importance as a cheap source of starch for fine quality brewing and in other diversified food uses. However, pearl millet being a crop grown and consumed by the poorest farmers needs nutritional bio-fortification by conventional and transgenic approaches to counteract the present nutritional deficiency in sub-Saharan Africa and parts of India.

Keywords: biofortification, crop breeding, nutrition, pearl millet, staple cereal

CONTENTS

INTRODUCTION

Pearl millet (*Pennisetum glaucum* (L.) R. Br.) is one of the earliest foods known to humans and has been a staple food for thousands of years in many parts of the world (Manning *et al*. 2010). The crop is highly tolerant to abiotic stressors like drought, salinity and high temperatures and therefore grown for grain and stover in the hottest and driest areas of Africa and South-Asia (Hash 2002). It is estimated that over 95% of pearl millet production is used as food, the reminder (5%) being divided between animal and poultry feed (ICRISAT 1997a) (**Fig. 1**).

Pearl millet annual production hits more than 29 million ha in the arid and semi-arid tropical regions of Asia, Africa and Latin America (ICRISAT 2002). Archaeobotanical evidence revealed the earliest domestication for food from the lower Tilemsi valley in Mali of sub-Saharan West-Africa, then predominantly cultivated across the region of Mauretania, Mali, Ghana, Burkina Faso, and Cameroun (Neumann 2005; Fuller 2007). Although being a very good food source and staple food crop that feeds many poor people, pearl millet is unfortunately not fully nutritional. Biotechnological approaches can pave ways to improve its food quality with various strategies.

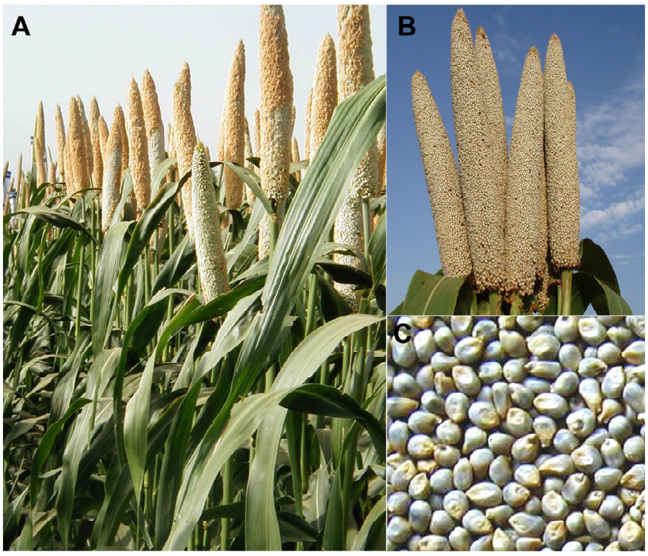

Fig. 1 (**A**) Pearl millet standing crop in farmer’s field, (**B**) pearl millet ear heads, (**C**) Pearl millet grain.

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Invited Mini-Review

Table 1 Proximate nutrient composition in pearl millet grain.

Composition (g/100 g)[a]		Minerals (mg/ 100 g)[b]		Essential amino acids (g/16 g N)[c]		Vitamins (mg/100 g)[b]	
Food energy (kJ)	1646-1691 (1733)[a]	Ca	41	Isoleucine	3.9-4.6 (4.6)[d]	Vitamin A (RE)[e]	24
Protein	8.6-19.4 (14.5)	Cl	47	Leucine	9.5-12.4 (9.3)	Thiamin	0.3
Starch	63.1-78.5 (71.6)	Cu	0.5	Lysine	2.8-3.2 (6.6)	Riboflavin	0.2
Fat	1.5-6.8 (5.1)	Fe	10.8	Phenylalanine+Tyrosine	7.1-9.3 (7.2)	Niacin	2.9
Dietary Fiber	8-9 (8.5)	Mg	125	Threonine	3.3-4.1 (4.3)	Vitamin E	1.9
Ash	1.6-3.6 (2.0)	Mn	0.8	Tryptophan	1.4-1.5 (1.7)		
		P	373	Valine	4.9-6 (5.5)		
		K	460	Cystine+Methionine	3.4-4.4 (4.2)		
		Na	17				

[a]Range and typical values; [b]Typical values; [c]Typical range; [d]Ideal pattern for infants; [e]Retinol equivalents
Source: Taylor 2004

NUTRITIONAL QUALITY

Nutritionally pearl millet is on a par with or even superior to most other cereals such as rice and wheat. The amino acid profile, vitamins, minerals, dietary fibers, and antioxidant phytochemcials are present in a more balanced ratio in pearl millet than in other cereals (Rai *et al.* 2008). The level of stored energy in pearl millet is approximately equal to that of maize (Amato and Forrester 1995), although with relatively higher oil content leading to better energetic feed than maize, wheat, or sorghum (Hill and Hanna 1990; Davis *et al.* 2003). Pearl millet has anti-nutritional factors than most grain crops. In contrast to rye and sorghum, pearl millet grain is low in tannins, which reduce protein availability; however, pearl millet can contain saponin anti-metabolites, however does not affect nutritional value (Andrews *et al.* 1996).

Pearl millet grains possess 27 to 32% higher concentration of essential amino acids, than maize, sorghum and wheat (Ejeta *et al.* 1987; Davis *et al.* 2003). The amino acid profile of pearl millet grain is better than that of sorghum or maize and is comparable to those of the small grains with a less disparate leucine/isoleucine ratio (Hoseney *et al.* 1987; Rooney and McDonough 1987), such as wheat, barley, and rice (Ejeta *et al.* 1987) (**Table 1**). Compared with maize, pearl millet has up to 60% higher content of crude protein, is about 40% richer in lysine and methionine and 30% richer in threonine (Burton *et al.* 1972). The lysine content of the protein reported in pearl millet grain ranges from 1.9 to 3.9 g/100 g protein (Ejeta *et al.* 1987). *P. glaucum* has high oil content (up to 4.2%) which consists of 50% unsaturated fatty acids; furthermore, it is rich in B vitamins, potassium, phosphorus, magnesium, iron, zinc, copper and manganese (Davis *et al.* 2003). Wetted grits pearl millet has characteristic odorous and flavored compound 2-acetyl-1-pyrroline (Seitz *et al.* 1993). Millet is characterized with arabino-xylans with xylose residues of α-(1,4)linkages and arabino-furanosyl residues of β-(1,3) linkages (Nandini and Salimath 2002). Moreover, it is provided with proteinaceous xylanase inhibitor to prevent hydrolysis of cell wall arabino-xylan by xylanases (Mokrane *et al.* 2009), that imparts crispness to flat bread. Bioavailability of zinc and iron is balanced with activity of native phytases on phytates in the flour (Agte and Joshi 1997; Lestienne *et al*. 2005a, 2005b). Soluble and bound phenolic extracts showed abundance of ferulic and p-coumaric acids as major hydroxycinnamic acids. Bound phenolics in millet contributed 38%-99% to ROS scavenging (Chandrasekara and Shahidi 2011).

Health benefits

Pearl millet, commonly known as bajra, offers many health benefits comparable to other cereals, fruits and vegetables. Pearl millet grains are all very high in calories, full of vitamins, minerals and amino acids precisely the reason they do ‘wonders’ for growing children and pregnant women (Parthasarathy Rao *et al*. 2006). The grain is easily digestible and has the lowest probability of causing allergic reactions (Dykes and Rooney 2007). It is rich in starch and this makes it a great source of energy. It is an excellent source of protein and fiber. Since it is gluten-free it helps people suffering from celiac disease. High potassium and magnesium in pearl millet helps in lowering blood pressure and maintenance of cardiovascular health (FAO 1995). Ensuring its intake in the diet, in the form of breads, porridges, biscuits and other cooked items, is highly effective and such diet is recommended in cases of severe constipation and stomach ulcers (Saikia 2011). The presence of phytic acid and niacin help in reducing cholesterol levels (Saikia 2011). It is also known to reduce the risk of cancer (Saikia 2011). Pearl millet seeds are also rich in phytochemicals like phytic acid (~0.825 mg) and phytate (~0.592 mg) per gram dry weight. High fiber content benefits for sufferers of diabetes due to the controlled blood sugar release in the bloodstream (Phanikumar 2010). Grain pearl millet diet induces a feeling of fullness and thereby aids in weight loss (INTSORMIL 2010). It is an alkaline and a warming grain i.e., it is not an acid forming food so is soothing and easy to digest, it will help to heat the body in cold or rainy seasons and climates, thereby making it a great, soothing choice for those suffering from constipation or other gut issues (FAO 1995; Leder 2004).

Live-stock

Poultry feed containing pearl millet grain rather corn had lower omega-6 to omega-3 fatty acid ratio, endowing the eggs with a fatty acid profile more favorable to human health (Collins *et al.* 1997; Amini and Ruiz-Feria *et al.* 2008). Forage brown midrib trait in pearl millet has improved forage quality by lowering amount of lignin and thus increased digestibility, which was tested by *in vitro* dry matter digestibility (IVDMD) and *in vivo* digestibility assays (Chemey *et al.* 1990; Sattler *et al.* 2010). Interestingly, cows fed with pearl millet silage produced milk with higher fat concentration (4.17% vs. 3.78%) than did cows fed with corn silage (Amer and Mustafa 2010). An analysis of the structure of the microbial community and the population dynamics by a pyrosequencing approach of tagged 16S rRNA gene amplicons from pearl millet-fermented slurries showed healthy presence of four phyla, with *Firmicutes* representing the highest diversity, followed by *Proteobacteria*, *Actinobacteria*, and *Bacteroidetes* (Humblot and Guyot 2009).

BIO-FORTIFICATION VIA CROP BREEDING

Nutrition

Pearl millet improvement is mainly done by traditional breeding. Traditional breeding procedures are time consuming and may take 8-10 years to transfer a trait from a donor species into a crop cultivar. Hybridization is one of the most effective means of incorporating selected genes into crop cultivars. However, this has several shortcomings like transmission of unwanted ‘alien’ chromosomes and adverse genetic interactions leading to sterility. Genetic engineering allows access to an unlimited gene pool independent of sexual compatibility. Recent biotechnological tools for direct gene transfer help to engineer new characters into plants, which are otherwise very difficult to transfer by conventional breeding programs (O’Kennedy *et al.* 2006; Rai *et* *al.* 2008). Superior crop cultivars have been developed by traditional plant breeding supplemented by marker assisted selection, hybridization along with manipulation of chromosome pairing. Conventional breeding should be supplemented with genetic transformation protocols to facilitate incorporation of important nutrition and resistance quality traits across the barriers of incompatibility (Gupta *et al.* 2001).

Breeding crops for better nutritional qualities is the main aim of bio-fortification. Bio-fortification technology apart from improving nutrition uptake in plants also helps host plants in defending plant diseases. It is essential to improve nutrition quality by agricultural-based strategies for poor farmers who solely rely on this crop. HarvestPlus, an agricompany, works with numerous partners around the world; in India, it is working with the Indian Council on Agricultural Research, the Government of India's Department of Biotechnology, International Crops Research Institute for the Semi-Arid Tropics, numerous regional universities and institutes, and other public and private sector partners. In Indian states Rajasthan, Maharashtra, Gujarat, and Uttar Pradesh where pearl millet is a staple food, an estimated 70% of children under five years are anemic, mainly due to iron deficiency (Smith 2011). A pearl millet variety with high-iron content is under release in India which is an improved version of an already released open-pollinated variety (ICTP 8203) in terms of iron and zinc content (HarvestPlus data 2011). Pearl millet flour was already fortified for zinc in the form of zinc stearate and the metal chelator EDTA as co-fortificant with a molar ratio Zn:EDTA (1:1) (Tripathi *et al.* 2010).

Consultative Group on International Agricultural Research (CGIAR) under its Bio-fortification Challenge program (CP)' HarvestPlus is addressing the issue of micronutrient malnutrition by crop breeding programs aiming at development of crops with enhanced levels of bioavailable essential minerals and vitamins (Bouis and Welch 2010; Bouis *et al.* 2011). Under this program, evaluation of pearl millet germplasm lines in semi-arid tropics of Asia and Africa revealed large variability for iron (Fe), zinc (Zn) and β-carotene (pro-vitamin A). Therefore, HarvestPlus identified pearl millet as one of the mandate crops for International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), to address this micronutrient deficiency problem and to develop pearl millet lines with high iron, zinc, and β-carotene content.

GB 8735, a progeny from a released variety, AIMP 92901, and a commercial seed parent 863B had high levels of Fe (68-82 mg kg^{-1}) and Zn (51-63 mg kg^{-1}), respectively HarvestPlus data 2010). It has been found that these Fe and Zn contents are highly stable characters in pearl millet. Studies also showed that from a 40-population trial in Niger, two lines, GB 8735 and GGP (both having an *iniari* landrace base like ICTP 8203 and AIMP 92901) were found to have the highest levels of Fe and Zn. One cycle of progeny-based recurrent selection in two populations (AIMP 92901 and GB 8735) improved the Fe levels by 11-12%, and Zn levels by 5-6%. A yellow-endosperm germplasm-derived line with high β-carotene (>130 μg/100 g grain) was also identified (HarvestPlus data 2010; http://www.harvestplus.org/content/pearl-millet-set-release-2012). The breeding trials are underway and product release will be done shortly.

Disease management

In India, efficiency and effectiveness of breeding programs are projected for improvement of hybrid pearl millet grain and stover yield. Seed parents are evaluated for hybrid production for yield stability across dry-land production environments in India. For example, hybrid HHB 67 that not only has superior host-plant resistance to pearl millet downy mildew disease caused by the oomycete plant pathogen *Sclerospora graminicola* (Sacc.) J. Schröt., but has improved resistance to rust caused by the basidiomycetic plant pathogen *Puccinia substriata* Ell. & Barth. var. *indica* Ramachar & Cumm., as well, and 25-30% higher mean grain yield than the original hybrid (Hash 2002). Transgenic approach has also been used to confer resistance to downy mildew by Girgi *et al.* (2006) using biolistic transformation. This group developed the first transgenic pearl millet with an antifungal protein (*afp*) gene from *Aspergillus giganteus* conferring resistance to downy mildew. Similarly, Latha *et al.* (2006) developed a transgenic pearl millet conferring resistance to downy mildew disease by inserting a chemically synthesized gene (*pin*) encoding a prawn antifungal protein.

CONCLUSION

Pearl millet is projected as a climate change compliant crop. It is a rich source of energy, protein, vitamins and minerals for the poorest of the poor. The beneficial properties of pearl millet in terms of nutrition and health play a major role in securing nutrition to the undernourished people and food-based health management, however, some to the best endowed lines lack in terms of iron and zinc content. Therefore, bio-fortification on pearl millet is a promising technology (Velu *et al.* 2007). In India, during green revolution, a major chunk of millet acreage was diverted to other crops, however, Indians are still the globe's largest consumers of all types of millets, eating 42% of the world's total production, followed by 26% in Nigeria, 10% in Niger, 7% in China, 5% in Burkina Faso, 4% in Mail, 2% in Russian Federation and the remaining in other countries. As health consciousness grows there is a tremendous rise in consumption of millets (http://www.outlookindia.com/article.aspx?264511).

More scientific technologies are required to improve pearl millet as an alternative model for cereal domestication in sub-Saharan Africa and parts of India (White and Broadley 2005). Given the current scenario with global warming and climatic changes, pearl millet has cultivation ability to grown under hot and dry conditions. ICRISAT, the International Crops Research Institute for the Semi-Arid Tropics is on fore front in developing pearl millet varieties with improved agronomic and processing quality. In Namibia, 'Okashana' variety, in India, Hybrid HHB 67 have proved their ability with high yield, early maturing and increased nutritional value (ICRISAT 1997b).

Critics of bio-fortification argue that bio-fortification through gene transfers might bring unknown consequences on crop and human health, it is time consuming and expensive (Palmgren *et al.* 2008). However, bio-fortification through genetic engineering and other biotechnology tools should be applied for fast development of pearl millet lines/ hybrids with enhanced nutritional qualities (Monyo 1998; Velu *et al.* 2007; Palmgren *et al.* 2008) in view of the importance of pearl millet crop which is a climate change compliant crop. Transgenic pearl millet with rich bio-fortified nutrients will contribute to the benefit of resource-poor people in the semi-arid regions, particularly when sophisticated comprehensive models of climate change have predicted that pearl millet is one among the winner corps that will gain increased land area suitable for its cultivation which is predicted to move to regions best equipped to manage the impacts of climate change (Lane and Jarvis 2007). Though the sustainability of bio-fortified crops remains a major challenge, bio-fortification *per se* is a potential and promising technology (Waters and Sankaran 2011; Zhao and Shewry 2011). There may appear additional criticisms and challenges as bio-fortified crops are unveiled in the coming years. But what we know is that these crops have tremendous promise, and education and awareness building around their introduction will be the key to make it available for people who need it.

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