Current Journal of Applied Science and Technology

Volume 42, Issue 48, Page 165-175, 2023; Article no.CJAST.112643
ISSN: 2457-1024
(Past name: British Journal of Applied Science & Technology, Past ISSN: 2231-0843, NLM ID: 101664541)

Deciphering the Importance of Underutilized Millet Crop towards Sustainable Feed and Food Sources

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Authors' contributions

This work was carried out in collaboration among all authors. Authors SI, MAB and TAS, designed the manuscript, prepared figures and arranged the references, and author ZAB organized and critically read the manuscript. The submitted version of the article was approved by all authors who contributed to it. All authors read and approved the final manuscript.

Article Information

DOI:10.9734/CJAST/2023/v42i484351

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy.Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://www.sdiarticle5.com/review-history/112643

Original Research Article

Received: 25/10/2023
Accepted: 29/12/2023
Published: 30/12/2023

ABSTRACT

The challenges posed by diminishing agricultural land, rapid urbanization, climate change, and the competition for resources between the food and feed industries have significantly constrained the availability of cultivable plant food sources. This scarcity is particularly acute in developing tropical countries, where resources often fall short in providing sufficient proteins for both human and animal consumption. However, there is substantial potential in the underutilized plant-derived materials, specifically millet crops, which are known for their protein richness and hold cultural significance,

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especially among tribal communities. The identification, assessment, and introduction of these underexploited millet crops offer a sustainable, long-term solution to ensure a steady supply of food and feed materials. The gluten-free millet grain family, with its tiny, spherical seeds, shows promise as a useful and plentiful food source. The name "millet" comes from the French word "mille," which means "a thousand," highlighting the possibility that a handful of grains may contain up to a thousand. With a 10,000-year history originating in Northern China, millets offer low fat, dietary energy, and glycemic index values along with nutritional advantages and resistance to pests and drought. These hardy crops include amino acids, dietary fibres, iron, zinc, calcium, phosphorus, potassium, vitamin B, and other essential elements. Notably, pearl millet's exceptional nutritional characteristics led the Indian government to classify it as a nutri-cereal in 2018 due to its remarkable nutritious qualities. The United Nations General Assembly has declared 2023 to be the "International Year of Millets," adding to the significance of millets. The Indian government declared 2018 to be the "Year of Millets." By highlighting the benefits of millets' nutrition, encouraging their growth, and incorporating them into regular meals, these programs want to raise awareness of the world's food and nutrition issues.

Keywords: Climate change; food security; millets; nutrition, drought.

1. INTRODUCTION

The diminishing agricultural land, swift urbanization, climate change, and intense competition between the food and feed industries for existing crops, particularly cereals, have constrained the availability of cultivable plant food sources. In developing tropical countries, these resources fall short in providing sufficient proteins for both humans and animals. Nonetheless, there lies potential in underutilized plant-derived materials, particularly millet crops, including those of tribal significance, known for their protein richness. Therefore, the identification, assessment, and introduction of these underexploited millet crops represent a sustainable, long-term solution for ensuring a steady supply of food and feed materials [1].Millet encompasses various gluten-free grains from different genera, featuring small, round seeds approximately 2–3mm in diameter, akin to mustard or coriander seeds [2]. The term "millet" finds its origin in the French word "mille," signifying a thousand, highlighting that a handful of millet can contain up to a thousand grains [3,4]. Millets are members of the grass subfamily Panicoideae, together with maize, sorghum, and Coix (Job's tears)[5]. Hence, all millets belong to the grass family (Poaceae or Gramineae) but are further divided into two tribes, Paniceae and Chlorideae [6]. The principal millet genera are pearl millet (*Pennisetum glaucum*), which accounts for 40% of world output, and foxtail millet (*Setaria italica*), which accounts for 20% [5], finger millet (*Eleusine coracana*) and proso millet, also known as white millet (*Panicum miliaceum*), make up the majority of millet output reported globally. According toPattanashetti [7]pearl millet is the type of millet that humans eat the most frequently since it produces the biggest seeds. Additional millets include Teff (*Eragrostis tef*), fonio (*Digitaria exailis*), guinea millet (*Brachiaria deflexa*), browntop millet (*Urochloa ramose*), kodo millet (*Paspalum scrobiculatum*), small millet (*Panicum sumatrense*), and barnyard millet (*Echinochloa spp.*) [2]. Millets hold the sixth position in global cereal grain production and are pivotal for food security in Africa and Asia, catering to millions of people [4,8]. “As one of the oldest foods cultivated since early human civilization, recent archeobotanical research indicates that common millet was domesticated as a staple food 10,000 years ago in Northern China” [9]. “Boasting drought and pest resistance, millets also offer nutritional benefits with low fat, dietary energy, and glycemic index values, along with documented health advantages. With almost 80% of the world's millet produced there, India is the world's top producer of the grain. The hard circumstances of rainfed farming, marginal soil fertility, and restricted rainfall are ideal for millets, which include great millet-sorghum, pearl millet-bajra, finger millet-ragi, foxtail millet, tiny millet, proso millet, barnyard millet, and kodo millet”[10]. “These hardy crops exhibit stability in yields and offer nutritional benefits, surpassing rice and wheat in protein content, while also providing dietary fibers, iron, zinc, calcium, phosphorus, potassium, vitamin B, and essential amino acids. Taking centre stage is pearl millet, which is India's fourth most significant grain crop after rice, wheat, and maize”[10]. With an average productivity of 1391 kg/ha, India is the world's top producer of pearl millet, generating 9.35 million tons from 7.41 million hectares. Almost 90% of the nation's pearl millet acreage is contributed by the main pearl millet-growing states of Rajasthan, Maharashtra, Gujarat, Uttar Pradesh, and Haryana combined. In regions where other main cereals find it difficult to grow, such as hot, dry areas with little to no rainfall (even as low as 250 mm), this climate-resilient C4 plant flourishes.A key crop that is robust to climate change, pearl millet is essential for reducing the negative effects of climate change and providing income and food security in dry regions [8]. In addition to having high levels of energy and carbs, its nutritional profile also includes high levels of fat (5-7%), ash (2.1%), dietary fibre (1.2g/100g), crude protein (13.6%), quality protein (8-19%), starch (63.2%), α-amylase activity, minerals (2.3mg/100g), vitamins A and B, antioxidants, and essential amino acids[11]. Notably, those with celiac disease can benefit from it because it is gluten-free. The Indian government designated pearl millet as a nutri-cereal in 2018 due to its remarkable nutritious qualities[12]. In addition, the United Nations General Assembly (UNGA) recognized 2023 as the "International Year of Millets," and the Government of India proclaimed 2018 as the "Year of Millets," acknowledging the importance of millets. These programs seek to draw attention to the nutritional benefits of millet, encourage its growing, and include it into regular meals, highlighting its role in tackling worldwide nutritional challenges.

2. GLOBAL MILLET PRODUCTION DYNAMICS

"Sorghum" and "millets" are the two independent categories in which FAOSTAT records global statistics on the area farmed, production output, and productivity of millets. It is noteworthy that pearl millet and tiny millets are included in the category of "millets". As such, our conversation will be split into two sections: the first will cover "sorghum," and the second will include the combined statistics for "pearl millet plus tiny millets[13]. Among the semiarid tropical crops, sorghum is particularly important; it is produced across an area of around 42.3 million hectares worldwide. Africa is home to the majority of the world's sorghum cultivation regions, accounting for 63.1% of all harvested land. The Americas give 16.2%, Asia follows with 18.5%. (Fig.1) [8]. "The top 10 countries in terms of sorghum acreage comprise seven in Africa (Sudan, Nigeria, Niger, Ethiopia, Burkina Faso, Mali and Tanzania), one in Asia (India) and two in the Americas (United States and Mexico). Sudan leads with a 17% share, followed by India (15%), Nigeria (13%) and others, contributing significantly to global sorghum cultivation. India boasts the largest sorghum acreage in Asia (6.2 million hectares), followed by China (0.6 million hectares) and Yemen (0.5 million hectares)"[14]. "Globally, sorghum production is estimated at around 61.5 million tons. The top 10 sorghum producers include the United States, Nigeria, Mexico, India, Sudan, Ethiopia, Argentina, Australia, Brazil and China, representing nearly 77% of global production and 70% of the harvested area. Africa and Asia combined constitute approximately 82% of the sorghum cultivation area and produce about 56% of sorghum grains. Among the top 10 producers, Argentina leads with the highest productivity (above 4000 kg/ha), followed by Australia, Mexico, the United States and China (3000–4000 kg/ha)"[14]. "Brazil and Ethiopia fall within the range of 2000–3000 kg/ha, while Nigeria records around 1200 kg/ha and India and Sudan lag with less than 1000 kg/ha. The global average sorghum productivity stands at around 1452 kg/ha" [15]. Analyzing trends from 1970 to 2009[16] found that the top 10 sorghum-producing countries experienced a drop in harvested area, with Asia and the USA recording the largest decrease. "However, grain yield levels increased substantially in all countries except Sudan. The analysis revealed an annual productivity growth of 0.96% across these top 10 countries relative to the 1970 yield levels. Pearl millet and small millets collectively span an extensive global cultivation area of 32.9 million hectares, yielding a production of 29.9 million tons. The majority of this cultivation area, around 63.5%, is situated in Africa, while Asian countries contribute 34.1% to the total area. European countries cover 1.5%, North America 0.8%, and Oceania 0.1% of the millet area" (Fig. 2) [17]. "Examining acreage distribution, the top 10 countries feature seven in Africa (Niger, Nigeria, Sudan, Mali, Burkina Faso and three in Asia (India, China, and Pakistan). India takes the lead with 28% of global acreage, followed by Niger (22%), Nigeria (12%), Sudan (8%) and others contributing varying percentages. Notably, Nigeria emerges as the largest producer in Africa, contributing 17% of world production, followed by Niger (10%), Mali, Burkina Faso and Sudan (4% each)"[18]. "India claims the top spot globally for both harvested area (9.2 million hectares) and production (10.9 million tons) of pearl millet. Remarkably, China boasts the highest productivity at 2250 kg/ha, followed by Ethiopia (1870 kg/ha), Nigeria (1316 kg/ha), and

India (1186 kg/ha)"[14]. "Pearl millet cultivation is prominent in Africa (over 14 million hectares) and Asia (over 12 million hectares)"[19]. India, in particular, commands an area of about 9.0 million hectares under pearl millet, contributing to over half of the world's pearl millet production. The productivity of pearl millet in India stands at 991 kg/ha. Globally, India takes the lead in small millets production, accounting for about 20% of the area dedicated to these crops. The annual planting area for small millets in India is approximately 2.5 million hectares.Over the past four decades, significant transformations have unfolded in the harvested area, production and productivity of pearl millet and small millets on a global scale. A comparative analysis spanning from 1970 to 2013 illuminates dynamic shifts in these key metrics across different continents. Notably, Asia and Europe have witnessed a decline in both harvested area (61% and 82%, respectively) and production (41% and 68%, respectively). In contrast, Africa has experienced an increase of 55% in harvested area and 47% in production, while the Americas saw a growth of 13% in harvested area and 35% in production (Fig. 2a,b). Over the four-decade period, there has been a global reduction of 27% in harvested area and 10% in production for pearl millet and small millets. However, amidst this trend, there is a notable upswing in productivity across all continents. Europe leads in this aspect, witnessing the highest percentage increase in productivity (726 kg/ha to 1282 kg/ha), followed by Asia (802 kg/ha to 1221 kg/ha) and the Americas (1125 kg/ha to 1620 kg/ha). This signifies a positive trend in the efficiency and yield of pearl millet and small millets cultivation over the years.Approximately 80% of millet grains serve as a crucial food source, while the remaining portion finds utility in animal fodder and the production of alcoholic beverages within the brewing industry[2].Millets play a vital role as a primary source of energy and protein for millions of individuals across China, Japan, Africa, and India, particularly benefiting those residing in hot and arid regions globally [20]. The global cereal production, estimated at 28,369,607 tons in 2017, was projected to rise to 31,019,370 tons in 2018. Leading the production chart were India (11,640,000 tons), Niger (3,856,344 tons), Sudan (2,647,000 tons), Nigeria (2,240,744 tons), Mali (1,840,321 tons), Mainland China (1,565,965 tons), Burkina Faso (1,189,079 tons), Ethiopia (982,958 tons), Chad (756,616 tons) and Senegal (574,000 tons) [21] (See Fig. 1). The major contributors to millet production are Asian and African countries, with Africa holding the majority share at 51%, followed by Asia at 47%, and minimal contributions from America (1%) and Europe (1%)[22] (Refer to Fig. 2a, b).In India, barley cultivation spans across approximately 9,107,000 hectares of land, resulting in a substantial millet production of 11,640,000 tons (FAO, 2018). These figures underscore the global significance of millets, not only as a staple food source but also as a versatile resource with diverse applications in agriculture and industry[23,24].

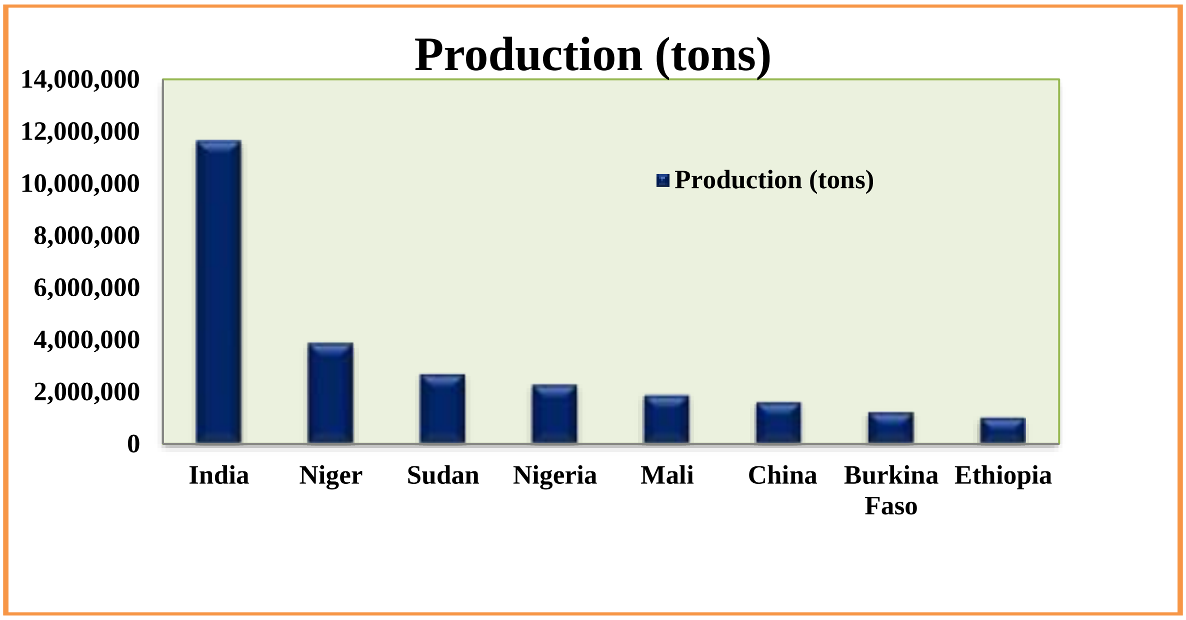

Fig. 1. Top millet producing countries worldwide FAO, 2018

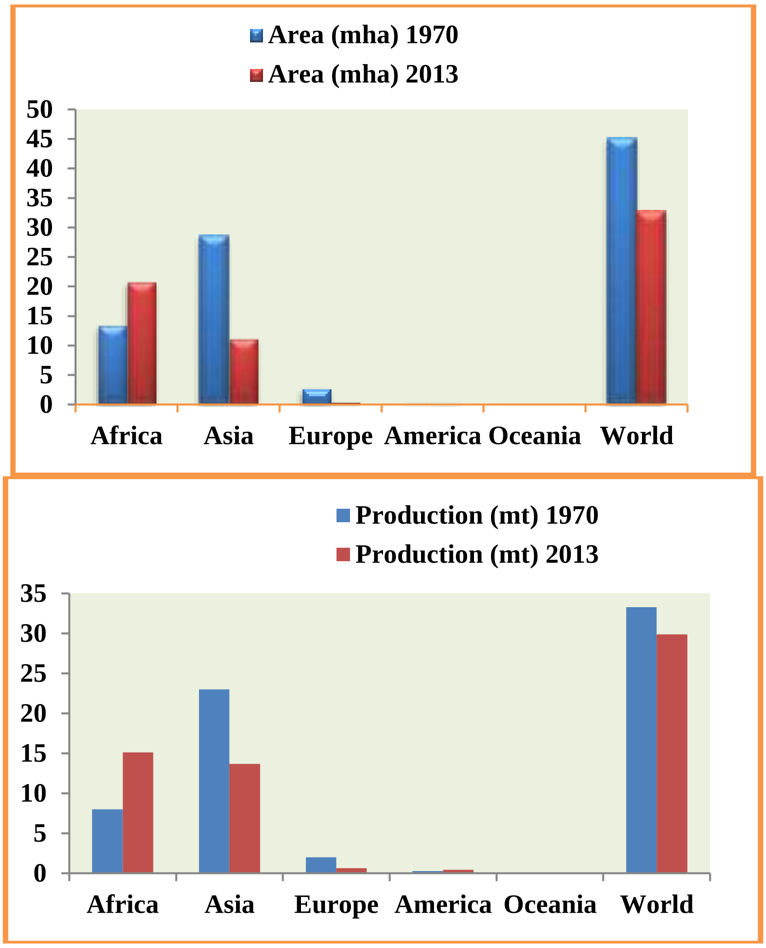

Fig. 2. changes in area (a) and (b)production of pearl millet and small millet in different continents over last four decades

3. IMPORTANCE OF MILLETS

3.1 Importance of Millets in Dry Land Agriculture

Dry land regions, encompassing over 40% of the Earth's terrestrial area, provide residence to a population exceeding two billion individuals. Primarily inhabited by some of the world's most economically disadvantaged communities, these areas heavily rely on millets as their primary staple food[25]. Millets thrive in agricultural conditions where other cereals struggle to yield a consistently acceptable harvest.The primary cultivation regions for millets in Africa and South Asia are characterized by an average annual rainfall ranging from 200 to 600 mm[25-27]. These areas typically exhibit distinctive features, including a brief rainy season lasting 2-4 months, elevated mean temperatures, high evapotranspiration rates and arid, shallow, sandy soils [28]. The growing season and productivity of millets thrive in challenging conditions characterized by dryness, high temperatures and poor soil quality. In semiarid tropics, where low precipitation and unfavorable soil conditions limit the cultivation of major food crops, millets demonstrate resilience and yield reasonable harvests[29]. Sorghum stands out as an exceptional rainfed crop, excelling in both grain and fodder production. Particularly in eastern and southern Africa, where low rainfall (43–180 mm/month) and moderate temperatures (16–26°C) prevail, about 35% of these regions face drought conditions, marked by warm temperatures (>20°C) and limited rainfall (<120 mm/month).In India, postrainy sorghum is cultivated in an area exceeding 5 million hectares, experiencing annual rainfall between 400 and 600 mm. Characterized by shallow to medium-depth soil (45–75 cm), limited rainfall (200–250 mm), cooler temperatures (12–20°C), and shorter days during the cropping season, postrainy sorghum relies heavily on stored moisture from the preceding rainy season and early-season precipitation. Pearl millet, well-suited for areas with drought conditions (rainfall 300–600 mm/year), low soil fertility and high temperatures (>35°C), thrives in regions with saline or acidic soils[29]. Notably, it can be grown in areas unsuitable for other cereals like maize or wheat, such as the arid zones of western Rajasthan, Haryana and Gujarat in India.Small millets exhibit broad adaptability, thriving in diverse soil and climatic conditions[30,31]. Finger millet, recognized for its resilience, proves to be an excellent crop for dry land conditions, requiring minimal water (400 mm/year). Proso millet, a short-duration crop well-suited to various soil and climatic conditions, boasts one of the lowest water requirements among cereals, making it ideal for dry land no-till farming. Kodo millet, known for its hardiness and drought tolerance, thrives in marginal soils where other crops might struggle, holding great potential to provide nourishing food for subsistence farmers in Africa and beyond[32].

3.2 Food and Nutritional Security

Despite advancements in agriculture and food production, the global population experiencing hunger has surpassed one billion[33,34]. The escalating demand for food poses a formidable challenge to achieving food security. From a worldwide standpoint, major cereals such as rice, wheat and maize play a significant role, followed by barley, sorghum, pearl millet, oat and rye[35]. The remaining cereals are categorized as minor millets. While sorghum and millets contribute only 1.08% and 2.21%, respectively, to the total food grain production globally [36] their importance in food and nutritional security extends beyond these figures. These crops play a crucial role in utilizing agricultural lands that might otherwise remain fallow.Millets hold particular significance as staple foods in numerous countries within semiarid tropics[13]. In regions characterized by low rainfall and poor soil fertility, where the cultivation of other major food crops is constrained, millets emerge as essential contributors to food and nutritional security[34,37]. Therefore, sorghum and Millets not only play a crucial role in global food production but are also indispensable in rainfed agro-ecosystems [37] These grains serve as valuable sources of high-energy and nutritious food, recommended for both children and adults. Generally categorized as nutria-cereals, millets stand out for their richness in fibers, minerals, and B-vitamins[38]. Foxtail millet, pearl millet and sorghum are particularly protein-rich (10.4–12.3 g per 100 g), while barnyard, kodo, foxtail, and proso millets boast high fiber content (7.6–9.8 g per 100 g). Finger millet excels in calcium content (344 mg per 100 g) and proso and pearl millets are notable sources of iron (8.0–9.3 mg per 100 g). Additionally, proso, barnyard and pearl millets are rich in zinc (3.0–3.7 mg per 100 g)[39,40]. Millets also contain phytochemicals beneficial to health. Sorghum serves diverse purposes, functioning as a staple in human diets, animal feed, and fodder and more recently, as a source of biofuels[41]. In Africa, sorghum grains undergo processing to create a variety of nutritious traditional foods, including semi-leavened bread, dumplings, couscous and various porridges. In central and southern parts of India, farmers utilize sorghum flour for crafting "jowar roti" a type of unleavened bread. The Indian market also features a range of ready-to-cook and ready-to-eat sorghum products, including value-added items like rawa, flakes, vermicelli, pasta and biscuits [42]. Beyond its role in human consumption, sorghum finds application in various industries. Sorghum grains are crucial feed for poultry, birds, and animals and they contribute to alcohol production in distilleries and starch-based products in the starch industry[41,43]. Developed countries like the United States and Australia primarily employ sorghum as animal feed. In India, the poultry feed sector utilizes around 1.30 million tons, the animal feed sector approximately 0.45 million tons and alcohol distillers about 0.09 million tons of sorghum grains annually [44].The postrainy sorghum cultivated in the semiarid regions of India holds significant value for its fodder. The food and nutritional security of animals in this region heavily relies on sorghum fodder, given that other crops seldom yield reasonable fodder under harsh growing conditions. In large regions of northern Nigeria, Niger, Mali and Burkina Faso, both sorghum and pearl millet serve as main staples. Pearl millet, in particular, is ground into flour for the preparation of large balls, sometimes liquefied into a watery paste using fermented milk and consumed as a beverage known as "fora" in Hausa. This beverage is popular in northern Nigeria and southern Niger[45]. Additionally, pearl millet stems find diverse uses, including the construction of walls and thatches, as well as the crafting of brooms, mats, and baskets. Small millets yield diminutive yet highly nutritious grains, known for their excellent storability, ensuring availability during times of crop failure for impoverished farmers. Finger millet holds particular value, containing the crucial amino acid methionine, which is often deficient in the diets of those reliant on starchy staples like cassava, plantain and maize meal. The grains of finger millet are ground and utilized in the preparation of cakes, puddings or porridge. Their exceptional malting property allows for the creation of high-value foods[46]. In regions such as Nepal and various parts of Africa, finger millet grains are employed to produce a fermented and flavored drink. Notably, finger millet stands out for its outstanding storage properties and nutritional value, surpassing rice and aligning closely with wheat. Additionally, finger millet serves as a rich source of micronutrients, including calcium, iron, phosphorus, zinc and potassium. Proso millet grains, devoid of gluten, are marketed as a health food and provide a suitable dietary option for individuals grappling with gluten intolerance. Sorghum serves various purposes, including food, feed, fodder and more recently, as a source of biofuels[47]. In Africa, sorghum grain undergoes processing to create a variety of nutritious traditional foods like semi-leavened bread, dumplings, couscous, and various porridges[46]. In central and southern parts of India, farmers utilize sorghum flour to make jowar roti, commonly known as "bhakri." The Indian market offers numerous ready-to-cook and ready-to-eat sorghum products, with value-added items like rawa, flakes, vermicelli, pasta and biscuits gaining popularity [42,47]. Beyond human consumption, sorghum has diverse industrial applications. Its grains serve as feed for poultry, birds and animals, and are used in alcohol production and starch-based products in the distillery and starch industry, respectively. In developed countries like the United States and Australia, sorghum primarily functions as animal feed[47]. The poultry feed sector in India currently utilizes around 1.30 million tons, the animal feed sector about 0.45 million tons and alcohol distillers about 0.09 million tons of sorghum grains annually. Post rainy sorghum grown in the semiarid regions of India holds high value for its fodder. The food and nutritional security of animals in this region heavily relies on sorghum fodder, as other crops seldom produce a reasonable fodder yield under harsh growing conditions. Sorghum and pearl millet serve as main staples in a vast region encompassing northern Nigeria, Niger, Mali, and Burkina Faso. Pearl millet, particularly significant across the Sahel, sees its grains ground into flour for the preparation of large balls. These balls are sometimes liquefied into a watery paste using fermented milk and consumed as a beverage known as "fora" in Hausa, a popular drink in northern Nigeria and southern Niger. Additionally, pearl millet stems find use in constructing walls, thatches and the creation of brooms, mats and baskets. Small millets yield petite grains that boast high nutritional value and excellent storability, ensuring availability for extended periods, thereby aiding poor farmers during crop failures. Finger millet holds particular significance due to its rich content of the essential amino acid methionine, often lacking in diets reliant on starchy staples like cassava, plantain and maize meal. The grains of finger millet are ground and cooked to produce cakes, puddings or porridge, while their excellent malting property allows for the preparation of high-value foods. In various regions, including Nepal and parts of Africa, finger millet grains are employed to create fermented and flavored drinks. This millet stands out for its exceptional storage properties, offering a nutritive value surpassing that of rice and comparable to wheat. Moreover, finger millet serves as a rich source of essential micronutrients such as calcium, iron, phosphorus, zinc, and potassium. Proso millet grains, devoid of gluten, are marketed as a health food, suitable for individuals grappling with gluten intolerance. Kodo millet, recognized for its nutritious profile, serves as an excellent source of fiber and harbors a high content of polyphenols, functioning as an antioxidant compound [48]. Other minor millets like tef and fonio find primary use in food items like porridges and flatbreads, possessing a limited malting potential[24]. In developed countries, millets play a diminished role as food sources. Notably, the significant millet crop in the United States is proso millet, predominantly cultivated for birdseed. Beyond their role in human nutrition, millets remain crucial as fodder sources for animals in semiarid regions. Domestic animals in dry areas heavily depend on millets for fodder, with sorghum and pearl millet being particularly vital, given the limited water availability in the soil[24].

3.3 Biofuel Production

The global emphasis on bioenergy as a renewable alternative to fossil fuels has led to intensive research on various grasses and oilseed plants for biofuel production. Among millets, a specially adapted type of sorghum known as "sweet sorghum" holds significant promise for bioenergy. This variant can accumulate high sugar levels in its juice-rich stalk, making it a favorable option for biofuel production[49]. Certain sweet sorghum lines can yield juice constituting about 78% of its total biomass and produce a substantial amount of grain[50,51].Sweet sorghum juice extracted from the stalks contains high fermentable sugars (15-23%) and it is estimated that sweet sorghum has the potential to produce 530-700 gallons of ethanol per acre[52,53]. It offers advantages such as lower cultivation costs compared to sugarcane, superior quality ethanol with lower sulfur, a high octane rating and compatibility with automobiles. The bagasse obtained after juice extraction is rich in micronutrients and can be utilized for power generation, generating approximately 2.5 MW per hectare[54,55]. Additionally, sweet sorghum can produce 3-4 tons of jaggery and 4 tons of syrup per hectare. Sweet sorghum serves as both a first and second-generation (lignocellulosic) biofuel due to its high content of soluble and structural sugars obtained from cellulose and hemicellulose[49]. Cellulose and hemicellulose content in high biomass sorghum lines range from 27% to 52% and 17% to 23%, respectively. Brown midrib lines, which contain less lignin, have garnered attention for second-generation biofuel production [56,57]. Rainy season sorghum grain, often damaged by mold infection, presents potential as a raw material for producing high-quality potable alcohol at a competitive cost compared to molasses. This development holds promise for new opportunities in agribusiness and employment generation in sorghum-growing regions in the semiarid tropics. Active research is ongoing in several countries to transform sweet sorghum into a commercially viable crop for ethanol production. Climate change is making its presence known globally, with agriculture taking a significant hit due to its heavy reliance on weather conditions. It's crucial to bolster the resilience of agriculture against climate variability and change, as the livelihood and security of millions of farmers hang in the balance[49,58]. Rising temperatures, unpredictable rainfall and a decrease in rainy days are clear signs of the shifting climate, underscoring the urgency of adapting agricultural practices to this new reality. Globally, climate change is becoming more and more noticeable and agriculture is suffering greatly as a result of its strong dependence on the weather. Supporting agriculture's resilience to climate variability and change is critical because millions of farmers' livelihoods and security are at risk[49,59,60]. The changing climate is evident in rising temperatures, erratic rainfall, and fewer rainy days, which emphasizes how urgently agricultural operations must adjust to this new reality. We expect problems including limited rainfall, protracted dry spells and high temperatures as a result of changing climatic patterns, especially in semiarid tropical regions. For farmers who rely on rain fed farming, this presents challenges because it can be difficult to estimate the best times to sow and harvest. Furthermore, changes in humidity and temperature might cause the formation of new diseases and pests[60,61]. The production of climate-resilient crops becomes imperative in response to these conditions and millets are one such crop that shows potential. Particularly notable drought-tolerant crops that provide significant yields on marginal and poor soils are pearl millet, sorghum and tiny millets[61]. Climate-resilient agriculture benefits greatly from the short growing season, heat tolerance and stress tolerance of pearl millet in particular. It outperforms maize and sorghum in regions with high temperatures and low soil fertility, thriving in areas where rainfall is insufficient for the cultivation of maize and sorghum[10]. Often referred to as the "Camel" of crops, pearl millet demonstrates exceptional drought tolerance, producing heat shock proteins in response to heat stress (35-45°C). Compared to many other cereals, pearl millet has a higher threshold temperature, allowing it to produce viable pollens even when other crops cease to do so under elevated temperatures[12,62]. Additionally, sorghum and pearl millet possess a natural ability to mitigate nitrous oxide (N_2O) emissions, a significant contributor to greenhouse gases and global warming. Through biological nitrification inhibition, the roots of sorghum and pearl millet can reduce the rate of nitrification, preventing the loss of nitrogenous fertilizer from the soil. This ecological characteristic makes them valuable allies in sustainable agricultural practices. Small millets emerge as resilient heroes in the face of drought and high temperatures, thriving in conditions where other crops struggle to survive. Excelling in poor soils and hotter, drier climates, they prove to be well-suited for challenging growing environments. Foxtail millet, in particular, stands out for its remarkable water use efficiency, needing only 257 g of water to produce 1 g of dry biomass— a notable contrast to the 470 g required by maize and 510 g by wheat [63]. Proso millet follows suit, demonstrating an impressive ability to convert minimal water into efficient dry matter and grain production. Millets are the most drought-tolerant cereals due to the low amount of input needed for growth, making them a sustainable choice in the face of depleting water resources and an expanding world population. Given these qualities, millets are appropriately referred to be "smart crops" or "climate-resilient crops since they are essential to ensure a resilient and sustainable agricultural future.

4. CONCLUSION

In order to propel millets into the mainstream of sustainable agriculture, it is imperative to address the multifaceted challenges hindering their widespread adoption. Specialized farming techniques, limited availability of quality seeds, pest and disease pressures, high production costs, low productivity, inadequate storage facilities, poor infrastructure, limited market access, low prices, unfavorable government policies and insufficient extension services collectively impede millet cultivation. To overcome these obstacles, collaborative efforts are essential. Investing in research and development for climate-resilient millet varieties, providing training and extension services for farmers, enhancing infrastructure, promoting market access and value addition, and implementing supportive government policies are crucial strategies. These endeavors aim to ensure the sustainable growth of millet production, fostering economic viability for farmers and bolstering agriculture's resilience in the face of climate challenges.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Nithiyanantham S, et al. Nutritional and functional roles of millets-A review. Journal of food Biochemistry. 2019;43(7):e12859.
2. Siroha AK, et al. Millets: Properties, processing, and health benefits; 2021. CRC Press.
3. Ramashia SE, Mashau ME, Onipe OO. Millets cereal grains: Nutritional composition and utilisation in Sub-Saharan Africa.IntechOpen London; 2021.
4. Shahidi F, Chandrasekara A. Millet grain phenolics and their role in disease risk reduction and health promotion: A review. Journal of Functional Foods. 2013;5(2):570-581.
5. Yang X, et al. From the modern to the archaeological: Starch grains from millets and their wild relatives in China. Journal of Archaeological Science. 2012;39(2):247-254.
6. Dvořáková Z, et al. Comparative analysis of genetic diversity of 8 millet genera revealed by ISSR markers. Emirates Journal of Food and Agriculture. 2015;617-628.
7. Pattanashetti, S.K., et al., Pearl millet, in Genetic and genomic resources for grain cereals improvement. Elsevier.2016;253-289.
8. Kheya SA, et al. Millets: The future crops for the tropics-Status, challenges and future prospects. Heliyon; 2023.
9. Lu H, et al. Earliest domestication of common millet (*Panicum miliaceum*) in East Asia extended to 10,000 years ago. Proceedings of the National Academy of Sciences. 2009;106(18):7367-7372.
10. Naresh R, et al. Millet: The super food in context of climate change for combating food and water security: A review. The Pharma Inno. 2023;12(3):1040-1049.
11. Jeena A, Rohit DC, Soe W. Millets for food and nutritional security in global climate change scenario. SOUVENIR; 2020.
12. Bandyopadhyay T, Muthamilarasan M, Prasad M. Millets for next generation climate-smart agriculture. Frontiers in Plant Science. 2017;8:1266.
13. Maitra S, Shankar T. Agronomic management in little millet (*Panicum sumatrense* L.) for enhancement of productivity and sustainability. International Journal of Bioresource Science. 2019;6(2):91-96.
14. Meena RP, et al. Global scenario of millets cultivation. Millets and Millet Technology. 2021;33-50.
15. Hoffman AL. Detecting the effect of dust and other climate variables on crop yields using diagnostic statistical crop models. The Pennsylvania State University; 2018.
16. Rakshit S, et al. Changes in area, yield gains, and yield stability of sorghum in major sorghum-producing countries, 1970 to 2009. Crop Science. 2014;54(4):1571-1584.
17. Dembélé S. Developing cultivation practicesto combat early drought challenges: The case of Sorghum in Mali. University of Cape Coast; 2016.
18. Gupta SM, et al. Finger millet: A “certain” crop for an “uncertain” future and a solution to food insecurity and hidden hunger under stressful environments. Frontiers in Plant Science. 2017;8:643.

19. Rouamba A, et al. Constraints to pearl millet (*Pennisetum glaucum*) production and farmers' approaches to striga hermonthica management in Burkina Faso. Sustainability. 2021;13(15):8460.
20. Amadou I, Gounga ME, Le GW. Millets: Nutritional composition, some health benefits and processing-A review. Emirates Journal of Food and Agriculture. 2013;501-508.
21. Taylor JR. Sorghum and millets: Taxonomy, history, distribution, and production, in Sorghum and millets. Elsevier.2019;1-21.
22. Verma NS, et al. Unveiling the nutritional spectrum of millet: An in-depth review. International Journal of Environment and Climate Change. 2023;13(11):2546-2559.
23. Mathad P, Ganachari A, Nidoni U. Millet industry scenario, in handbook of millets-processing, quality, and nutrition status. Springer. 2022;343-366.
24. Sukumaran Sreekala AD, et al. Millet production and consumption in India: Where do we stand and where do we go? National Academy Science Letters. 2023;46(1):65-70.
25. Maitra S. Intercropping of small millets for agricultural sustainability in drylands: A review. Crop Research. 2020;55(3and4):162-171.
26. Prăvălie R. Drylands extent and environmental issues. A global approach. Earth-Science Reviews. 2016;161:259-278.
27. Bidinger FR, Hash CT. Pearl millet. Physiology and biotechnology integration for plant breeding. 2004;225-270.
28. Windmeijer P, Andriesse W, Inland valleys in West Africa: An agro-ecological characterization of rice-growing environments.ILRI; 1993.
29. Pandey A, Bolia NB. Millet value chain revolution for sustainability: A proposal for India. Socio-Economic Planning Sciences. 2023;101592.
30. Sharmili K, et al. Millet and pulse-based intercropping system for agricultural sustainability-A review. Crop Research. 2021;56(6):369-378.
31. Maitra S, et al. Agronomic management of foxtail millet (*Setaria italica* L.) in India for production sustainability: A review. International Journal of Bioresource Science.2020;7(1):11-16.
32. Dwivedi N, Rathore V, Sharma K. A review of millet crops for agricultural sustainability in India. Asian Journal of Agricultural Extension, Economics & Sociology. 2023;41(10):216-224.
33. Pragya S, Rita SR. Finger millet for food and nutritional security. African Journal of Food Science. 2012;6(4):77-84.
34. Rai RK, et al. A life-cycle approach to food and nutrition security in India. Public health nutrition. 2015;18(5):944-949.
35. Renganathan VG. et al. Barnyard millet for food and nutritional security: current status and future research direction. Frontiers in Genetics. 2020;11:500.
36. Das IK, Rakshit S. Chapter 1 - millets, their importance, and production constraints, in biotic stress resistance in millets, I.K. Das and P.G. Padmaja, Editors. Academic Press. 2016;3-19.
37. Upadhyaya HD, Vetriventhan M. Underutilized climate-smart nutrient rich small millets for food and nutritional security; 2018.
38. Muthamilarasan M, Prasad M. Small millets for enduring food security amidst pandemics. Trends in Plant Science. 2021;26(1):33-40.
39. Kumar A, et al. Millets: A solution to agrarian and nutritional challenges. Agriculture & Food Security. 2018;7(1):1-15.
40. Murugesan R, Use of millets for partial wheat replacement in bakery products. McGill University (Canada); 2015.
41. Arya C, Bisht A. Small millets: Path to food and nutrition security, in small millet grains: The superfoods in human diet. Springer. 2022;161-190.
42. Patel I, Dharaiya C, Pinto S. Development of technology for manufacture of ragi ice cream. Journal of Food Science and Technology. 2015;52:4015-4028.
43. Ramachandran P. Food & nutrition security: Challenges in the new millennium. The Indian Journal of Medical Research. 2013;138(3):373.
44. Singh RP, et al. Millets for food and nutritional security in the context of climate resilient agriculture: A Review. International Journal of Plant & Soil Science.2022;939-953.
45. Narayanan S, Gerber N. Social safety nets for food and nutrition security in India. Global food Security. 2017;15:65-76.
46. Wilson ML, VanBuren R. Leveraging millets for developing climate resilient agriculture. Current Opinion in Bio-technology.2022;75:102683.

47. Ashoka P, Gangaiah B, Sunitha N. Millets-foods of twenty first century. Int. J. Curr. Microbiol. Appl. Sci. 2020;9:2404-2410.
48. Hegde PS, Chandra T. ESR spectroscopic study reveals higher free radical quenching potential in kodo millet *(Paspalum scrobiculatum)* compared to other millets. Food Chemistry. 2005;92(1):177-182.
49. O'Kennedy MM, Grootboom A, Shewry P. Harnessing sorghum and millet biotechnology for food and health. Journal of Cereal Science. 2006;44(3):224-235.
50. Yadav M, Vivekanand V. Combined fungal and bacterial pretreatment of wheat and pearl millet straw for biogas production–a study from batch to continuous stirred tank reactors. Bioresource Technology. 2021;321:124523.
51. Reddy VG, Upadhyaya H, Gowda C. Characterization of world's foxtail millet germplasm collections for morphological traits. International Sorghum and Millets Newsletter. 2006;47:107-109.
52. Elinge CM, et al. Effect of Millet Stalks and Shea Nut Shells on Biogas Production. The Journal of Solid Waste Technology and Management. 2021;47(2):292-296.
53. Balodis O, Bartuševics J, Gaile Z. Biomass yield of different plants for biogass production. in environment. technologies. Resources. Proceedings of the International Scientific and Practical Conference; 2011.
54. Kumar S, et al. Weak alkaline treatment of wheat and pearl millet straw for enhanced biogas production and its economic analysis. Renewable Energy. 2019;139:753-764.
55. Das I, Rakshit S. Millets, their importance, and production constraints, in Biotic stress resistance in millets. Elsevier. 2016;3-19.
56. Oliver AL, et al. Comparative effects of the sorghum bmr-6 and bmr-12 Genes: II. Grain yield, stover yield, and stover quality in grain sorghum. Crop Science. 2005;45(6):2240-2245.
57. Shi CF, et al. Short-term effects of biogas residue on millet properties, soil properties and microbial functional diversity in saline soil. Journal of Biobased Materials and Bioenergy. 2020;14(1):108-113.
58. Priya G, Sathyamoorthi K. Influence of organic manures on the growth and yield of foxtail millet [*Setaria italica* (L.) Beauv]. Chem Sci Rev Lett. 2019;8(29):114-7.
59. Saxena R, et al. Millets for food security in the context of climate change: A review. Sustainability. 2018;10(7):2228.
60. Maitra S, et al. Small millets: The next-generation smart crops in the modern era of climate change, in Omics of climate resilient small millets. Springer. 2022;1-25.
61. Wang J. et al. Effect of climate change on the yield of cereal crops: A review. Climate.2018;6(2):41.
62. Singh P, et al. An assessment of yield gains under climate change due to genetic modification of pearl millet. Science of the Total Environment. 2017;601:1226-1237.
63. Diao X. Production and genetic improvement of minor cereals in China. The Crop Journal. 2017;5(2):103-114.

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