

Millets Based Integrated Farming System for Food and Nutritional Security, Constraints and Agro-diversification Strategies to Fight Global Hidden Hunger: A Review

Abstract:

Due to the prevalence of hidden hunger, a type of malnutrition brought on by a lack of certain micronutrients, the situation regarding global food and nutritional security has recently come under scrutiny. In order to address these issues and lessen worldwide hidden hunger, this research investigates the possibilities of millets-based integrated farming systems. Small-seeded grains known as millets are renowned for their great nutritional value and resistance to a variety of agro-ecological situations. Millets have however seen a drop in cultivation and consumption in many countries despite their nutritional potential because of a variety of issues. The limitations of millets-based integrated agricultural systems are highlighted in this paper, including limited access to better seed varieties, a lack of post-harvest infrastructure, shaky market relations, and insufficient policy backing. Millets are underutilized as a result of these limitations, which limits their ability to reduce hidden hunger and enhance food and nutritional security. This report offers numerous important suggestions for overcoming these limitations and encouraging agro-diversification initiatives. These include stepping up research and development to improve the adaptability and nutritional value of millet varieties, putting policies in place that support millet marketing and production, setting up a productive post-harvest infrastructure, and raising consumer awareness of and demand for millet-based products. In addition, encouraging cooperation among many stakeholders, including farmers, researchers, policymakers, and consumers, is essential to create a favourable climate for the adoption and expansion of integrated agricultural systems based on millets. Embracing millets as a cornerstone of integrated farming systems allows for the diversification of agricultural methods, which improves ecosystem services such as soil health and biodiversity. Additionally, the nutritional advantages of millets, such as their high fibre, protein, and micronutrient contents, can considerably help to combat hidden hunger and ensure global food and nutritional security.

Keywords: *millets, integrated farming systems, food security, nutritional security, hidden hunger, agro-diversification, soil health, biodiversity.*

Introduction:

“Tackling hunger and feeding the world population are two of the biggest challenges of the modern world. Reasons contributing to this issue range from deficiencies in the supply of micro- and macro-nutrients, shortage in production of foods leading to supply–demand

imbalances, and conflicts destabilize various parts of the world. Although several of these triggers for hunger can be addressed leading to a slight reduction in the population suffering from hunger and malnutrition from almost one billion in 1990–1992 to 850 million in 2010–2012, the threat of climate change and global warming still lingers” (**Kumar et al., 2022**). One of the largest problems facing the modern world is feeding everyone on the planet. The lack of micro- and macronutrients, shortages in food production that cause supply-demand mismatches, and conflicts that destabilize different regions of the world are all factors that contribute to this problem. Even though some of these causes of hunger can be addressed, the threat of climate change and global warming still exists. As a result, the number of people who experience hunger and malnutrition has decreased slightly from approximately one billion in the years 1990–1992 to 850 million in the years 2010–2012 (**FAO, 2012**). 2-3 billion people may experience nutritional insecurity as a result of reduced food production rates and the additional strain of feeding a population that will top 9 billion by 2050 (**Naresh et al., 2023**). Food and nutritional security remain a critical global challenge in the 21st century. With the world population projected to reach 9 billion by 2050, ensuring adequate and nutritious food for all has become a pressing concern. Concurrently, the issue of hidden hunger, characterized by micronutrient deficiencies despite sufficient caloric intake, poses a grave threat to the well-being and development of millions of people worldwide. To address these challenges, a sustainable and diversified approach to agriculture is imperative, aiming to improve not only food production but also nutritional content. Millets come in a variety of small-seeded species, including finger millet (*Eleusine coracana*), proso millet (*Panicum miliaceum*), little millet (*Panicum sumatrense*), foxtail millet (*Setaria italica*), and pearl millet (*Pennisetum glaucum*). In addition to sorghum (*Sorghum bicolor*), maize (*Zea mays*), barley (*Hordeum vulgare*), and oats (*Avena sativa*), they are referred to as coarse cereal (**Bhatt et al., 2023**). The largest producer of millet grains in the world, with an annual production of 334500 tonnes (43.85 %), was India, with a total global millet grain production of 762712 metric tonnes. Millet provides food, economical, and animal feed stability. Millets, a group of small-seeded cereal grains, have garnered increasing attention as a potential solution to food and nutritional security. These crops have been cultivated for millennia and have shown remarkable resilience to harsh environmental conditions, making them well-suited for diverse agro-climatic regions. Moreover, millets possess high nutritional value, being rich in protein, dietary fiber, essential minerals, and vitamins. Integrating millet-based farming systems offers a unique opportunity to combat hidden hunger while ensuring sustainable agricultural practices.

Agriculture productivity is adversely affected with serious impact on production and productivity due to uneven weather conditions increased temperature and less availability of

irrigation water. Global climate change together with the rapidly increasing population is mounting considerable pressure on agriculture sector to produce more food from less land. The anticipated increase in temperature will mostly affect the hot tropics, mainly populated by developing countries as they are likely to suffer maximum loss in food production (**Cline, 2007**). Even in temperate regions, several strategies need to be devised for the adaptation of agricultural crops against erratic climate conditions such as changing temperature, erratic rainfall, and onset of severe floods and droughts (**Meehl et al., 2007**). It has been anticipated that climate change may severely impact food production and food security in several drought-prone regions across the globe (**Agriculture Organization of the United Nations. Economic, & Social Department, 2005**). This water paucity is leading to shrinking of dietary range and reduction of total food consumption that could possibly lead to malnutrition problems and food insecurity (**Intergovernmental Panel on Climate Change [IPCC], 2007**). A key issue is whether we will be able to feed the projected global population of 9 billion in 2050 equitably, healthily and sustainably (**Beddington, 2010**). Even if a person consumes enough calories, it is likely that he may have an inadequate consumption of vital micronutrients such as vitamins, minerals and trace elements leading to micronutrient undernourishment or what can be termed as hidden hunger. Pests and diseases are also likely to be greatly impacted by changing temperatures (**Stireman et al., 2005**).

Thus, development of varieties with enhanced nutraceutical value and improved stress tolerance has been one of the priority areas of research these days. Modern crop improvement techniques such as genomics-assisted breeding and genetic engineering play important role in understanding the complexities of stress response and tolerance as well as in providing measures for enhanced crop productivity. However, one of the possible solutions to counter these tribulations can be identifying and improving native crops that are highly adaptive to local climate, have high nutritive value and can efficiently withstand biotic and/or abiotic stresses. Although it is difficult to find a single staple food crop that fulfils all the major criterions, the wide variety and diversity of local food crops (such as minor millets) provide us a choice of such climate resilient crops (**Shukla et al., 2015**). As India's agriculture suffer hugely from the vagaries of monsoon, millets which are also known as "famine reserves" for their prolonged and easy storability under ordinary are of great relevance. They are most suitable for mixed and intercropping, thus offer sustainable resources use, food and livelihood security to farmers. Millets, which are grown for both food and fodder, increase farming's economic efficiency and enhance the safety of food and livelihood for millions of households, especially small and marginal farmers and people living in remote tribal areas with limited access to water. According to research, a 1% increase in production might cut poverty by 0.65%. As rain-fed areas are 30% less productive than

irrigated areas, increasing production is especially crucial in these areas. Millets appear to hold the key to fighting poverty, malnutrition, and climate change (Tiwari *et al.*, 2022).



(Source: Tiwari *et al.*, 2023a)

Figure 1. Characteristic features of millets

Table 1. Nutrient composition of millets (per 100 g):

Millets	Carbohydrates (g)	Protein (g)	Fat (g)	Energy (kcal)	Crude fibre (g)	Mineral matter (g)	Ca (mg)	P (mg)	Fe (mg)
Finger	72.0	7.3	1.3	328	3.6	2.7	344	283	3.9
Kodo	66.9	8.3	1.4	309	9.0	2.6	27	188	0.5
Proso	70.4	12.5	1.1	341	2.2	1.9	14	206	0.8
Foxtail	60.9	12.3	4.3	331	8.0	3.3	31	290	2.8
Little	67.0	7.7	4.7	341	7.6	1.5	17	220	9.3
Barnyard	65.5	6.2	2.2	307	9.8	4.4	20	280	5.0
Sorghum	72.6	10.4	1.9	349	1.6	1.6	25	222	4.1
Bajra	67.5	11.6	5.0	361	1.2	2.3	42	296	8.0

Table 2. Vitamin profile of millets:

Millets	Thiamin(mg)	Niacin (mg)	Riboflavin	Vit B6 (mg/100 g)	Folic acid (mg/100 g)	Vit B5 (mg/100 g)	Vit E (mg/100 g)
Foxtail	0.59	3.2	0.11	–	15.0	0.82	31.0
Proso	0.41	4.5	0.28	–	–	1.2	–
Finger	0.42	1.1	0.19	–	18.3	–	22.0
Little	0.3	3.2	0.09	–	9.0	–	–
Barnyard	0.33	4.2	0.1	–	–	–	–
Kodo	0.15	2.0	0.09	–	23.1	–	–
Sorghum	0.38	4.3	0.15	0.21	20.0	1.25	12.0
Bajra	0.38	2.8	0.21	–	45.5	1.09	19.0

Table 3. Essential amino acid profile of millets (mg/g of N):

Millets	Arginine	Histidine	Lysine	Tryptophan	Phenyl alanine	Tyrosine	Methionine	Cystine	Threonine	Leucine	Isoleucine	Valine
Foxtail	220	130	140	60	420	–	180	100	190	1040	480	430
Proso	290	110	190	50	310	–	160	–	150	760	410	410
Finger	300	130	220	100	310	220	210	140	240	690	400	480
Little	250	120	110	60	330	–	180	90	190	760	370	350
Barnyard	270	120	150	50	430	–	180	110	200	650	360	410
Sorghum	240	160	150	70	300	180	100	90	210	880	270	340
Bajra	300	140	190	110	290	200	150	110	140	750	260	330

Table 4. Micronutrient profile of millets (mg/100 g):

Millets	Mg	Na	K	Cu	Mn	Mb	Zn	Cr	Su	Cl
Foxtail	81	4.6	250	1.40	0.60	0.070	2.4	0.030	171	37
Proso	153	8.2	113	1.60	0.60	–	1.4	0.020	157	19
Finger	137	11.0	408	0.47	5.49	0.102	2.3	0.028	160	44
Little	133	8.1	129	1.00	0.68	0.016	3.7	0.180	149	13
Barnyard	82	–	–	0.60	0.96	–	3	0.090	–	–
Kodo	147	4.6	144	1.60	1.10	–	0.7	0.020	136	11
Sorghum	171	7.3	131	0.46	0.78	0.039	1.6	0.008	54	44
Bajra	137	10.9	307	1.06	1.15	0.069	3.1	0.023	147	39

Table 5. Fatty acid composition and amylose and amylopectin content profile of millets:

Millets	Palmitic	Palmeolic	Stearic	Oleic	Linoleic	Linolenic	Amylose (%)	Amylopectin (%)
Foxtail	6.40	–	6.30	13.0	66.50	–	17.5	82.5
Proso	–	10.80	–	53.80	34.90	–	28.2	71.8
Finger	–	–	–	–	–	–	16.0	84.0
Little	–	–	–	–	–	–	–	–
Sorghum	14.0	–	2.10	31.0	49.0	2.70	24.0	76.0
Bajra	20.85	–	–	25.40	46.0	4.10	21.1	78.9

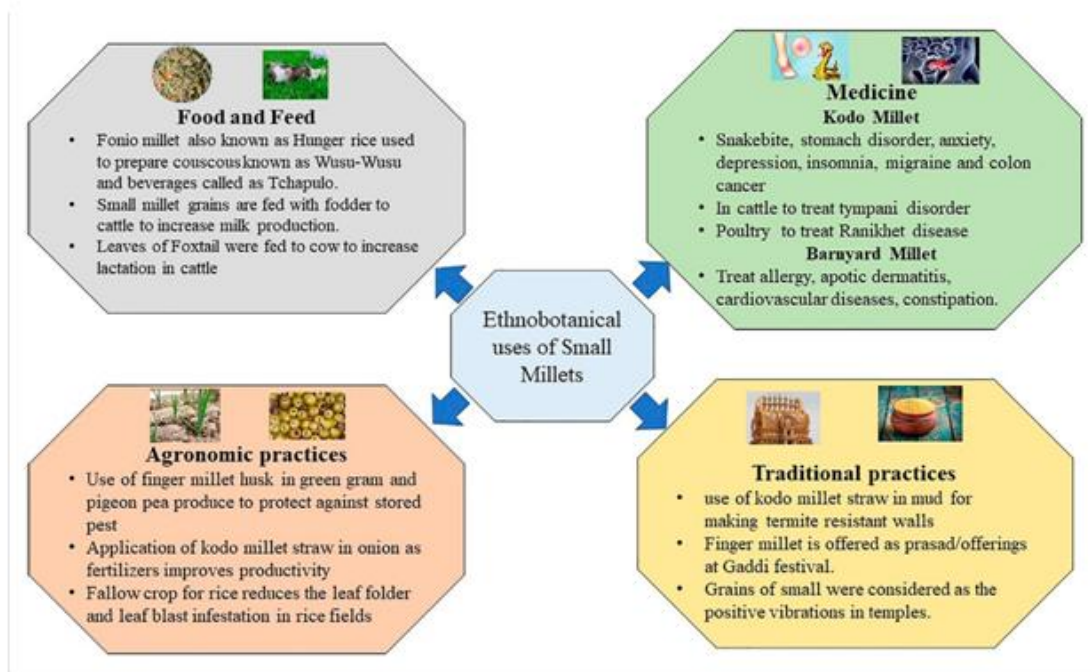
(Source: Tiwari *et al.*, 2023b)

Ethnobotanical values of millets:

Millets have a profound significance in our cultural heritage and until now have played significant roles in temple festivals. These activities are preserved as traditional knowledge in the regulations put forth by PPVFRA, 2001 (Satyarthi *et al.*, 2018). These traditions demonstrate that these grains were recognized by our ancestors for their nutraceutical and therapeutic values (Figure 2). One common practice in small grains was their presentation as a wedding gift to the bridegroom. The number of grains gifted was treated as a prestige; the grains were also cooked, especially during puberty and childbirth celebrations (Rawat *et al.*, 2021). Millets are rich in folic acid; therefore, they were treated as a special entity for women to overcome anaemic disorders. In Africa, fonio millet, commonly known as “hungry rice,” has similar importance. These grains are predominantly used to prepare couscous known as wusuwusu. Fonio is best used in the preparation of beverages called Tchapulo, which is rich in minerals. Finger millet has a similar value in the processing of beer, and its

malted products are often used in African tribal communities (**Hitu et al., 1997**). Arake, a distilled liquor, is prepared in Ethiopia with finger millet flour. Furthermore, people residing in Sudan predominantly consume a hot porridge of finger millet with banana or sugar juice, which is a staple dish in tribal zones. A sour bread known as injera is made from teff and is used in spicy stews by well-off tribal individuals. Teff has a unique role in Africa after fonio millet. Due to its cold tolerance in higher altitudes, it is popularly known as love grass. The novel features of these lost crops are also being conserved. The major morphotypes in fonio millet are Yoro, Ipordapia, Ipordawoun, Ipoagoa, and Iporni are conserved by communities including the Hausa and pagans in west African regions (**Dansi et al., 2010; National Research Council, 1996**). Regarding the conservation of cultural heritage in India, the Malayali in Eastern Ghats continue to cultivate and conserve small millet landraces (**Newmaster et al., 2013**). The landraces of little, foxtail, and proso millets are conserved by the Kolli Hill tribes; the characteristics of these millets suggest the presence of novel alleles for future breeding programs (**Venkatesan et al., 2015; Ragupathy et al., 2016**). Tracking the records of the utilization of millets in Chhattisgarh, India has revealed the use of Kodo millet straw in mud to make termite-resistant walls. The farmers of this region also used Kodo millet straw as fertilizers in onion fields to increase productivity. Another traditional practice was the application of finger millet husk in green gram and pigeon pea products to protect these grains from pest infestation during storage. The pot makers in Northern India also are using Kodo millet straw when baking pots. Moreover, the leaves of Kodo millet possess lecithin and are used for the treatment of snakebites, stomach disorders, and joint pain. In cattle, Kodo millet straw had a significant impact on treating tympani disorder. Additionally, the older grains of Kodo millet (3–4 years) were used to cure Ranikhet disease in poultry. In Africa and India, Kodo millet was a fallow crop after rice; in other rice fields, Kodo millet straw is usually spread in the fields to protect against leaf folder and blast (**Rawat et al., 2021**). The millet grains were also previously mixed with fodder to increase milk production in cows. Several recent agro-start-ups in India for cattle feed also practice this technique to enhance milk production in rural dairy farms (**Bhat et al., 2018**). In traditional practice, finger millet is often a prasad/offering in the Gaddi festival. This is believed to enhance the fruiting of non-flowering mango and tamarind trees. Furthermore, thick pastes of finger millet flour are used to treat fire burns, and these grains are considered to offer positive energy in temples (**Sahu and Sharma, 2013**). In addition, barnyard millet is used to treat allergies, atopic dermatitis, cardiovascular diseases, constipation, and blood-related disorders. Moreover, Kodo millet is preferred for overcoming anxiety, depression, insomnia, migraine, and colon cancer. Foxtail millet is used to treat chicken pox, heart attack, fever, cholera, and gastric problems. The leaves of foxtail millet are also fed to cattle to increase lactation. These practices underscore the nutritional and therapeutic value

of small millets in our heritage. The genetics underlying these traits could be explored and used to develop sustainable diets (Satyarthi *et al.*, 2018).



(Source: Lydia *et al.*, 2023)

Figure 2. Ethnobotanical values of millets

UNDER PEEER

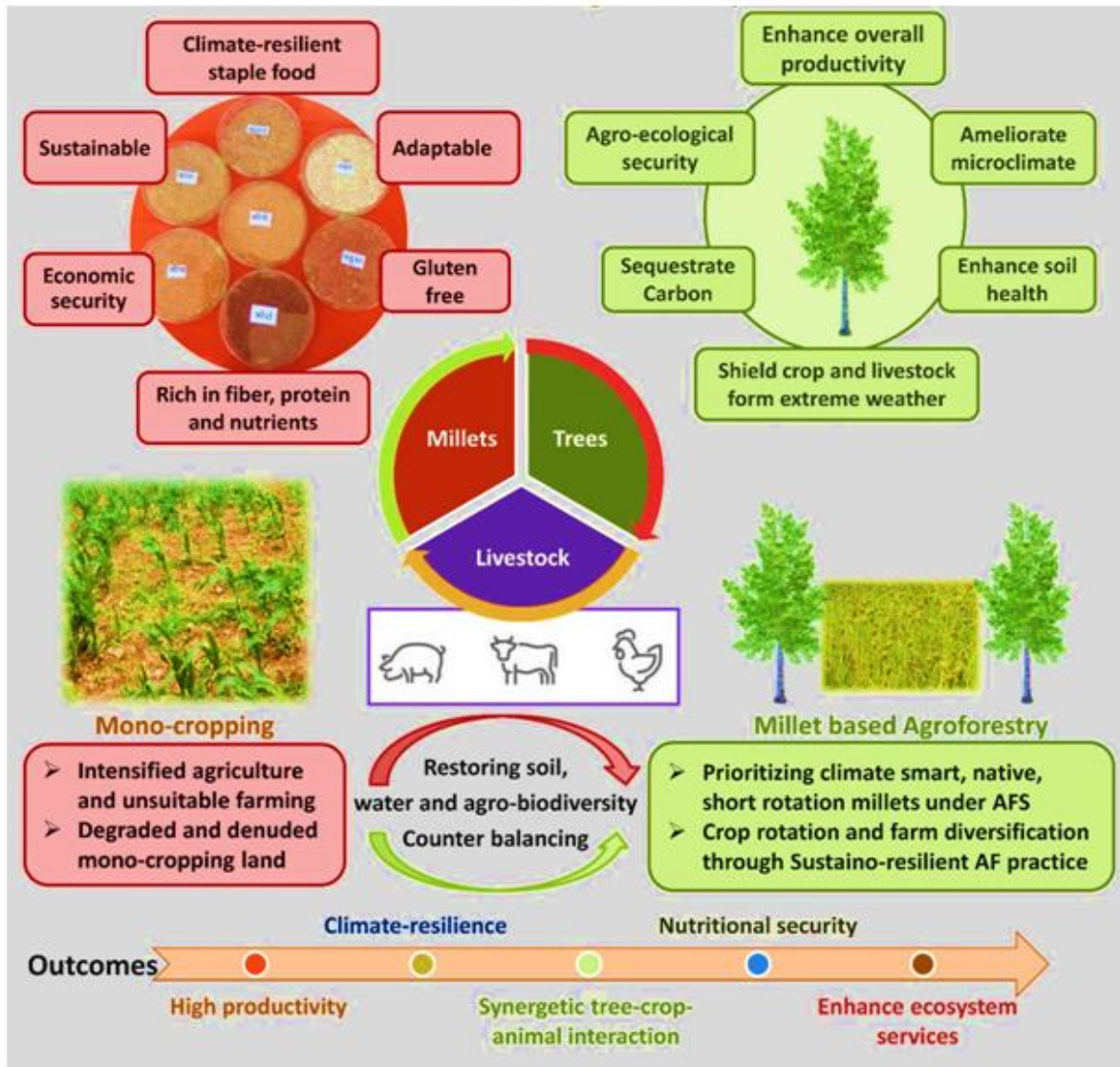


Figure 3. Millets Based Integrated Farming System

(Source: Teli, 2023)

Millet-based Integrated Farming System (Mb IFS) is a climate resilient and sustainable system that combines tree-crop-livestock on the same area of land (Bado *et al.*, 2021). Growing crops along with trees offer numerous economic advantages since the trees support crops and livestock as well as a variety of ecological services. Along with its primary economic advantages, MbIFS may also contribute to nutritional security and mitigation of climate change (Handa *et al.*, 2019; Soam *et al.*, 2022).

Technology Interventions

There is a large scope for increasing productivity and profitability for farmers through scaling-up of climate resilient agriculture; however, it calls for concerted efforts, adoption of location-specific and cost-effective technologies. The new technologies should also be less input intensive, cost-effective, less labour intensive and economically viable. Based-on experience

of millets cultivation, some promising interventions are underlined (**Chapke and Tonapi, 2018**).

1. Promotion of allied enterprises as integrated farming system

Since, the mono-cropping and traditional farming are not viable, addressing only a component of the farming system, e.g., crop variety, fertilizer use or even crop husbandry per se is not expected to bring about a significant increase in the productivity as witnessed in irrigated areas. The soil, plant, animal cycle is the basis for all feed used by the animals. The livestock in the rainfed regions are weak. Farmers in this area often sell their cattle due to the scarcity of fodder. The land holdings are being reduced with increased population pressure. There is large unexploited scope to harness system level productivity and value chains, wherein women have income generating opportunities through women-focused activities. Therefore, the millets-based integrated farming system approach with introduction of poultry, dairy, goat farming, piggery and apiculture at each household will help to supplement the farmers' income and women empowerment.

2. Millets-based inter cropping

To achieve appropriate land use, efficient inter- and sequence-crop systems were recommended based-on soil type, rainfall and length of growing seasons. Intercropping sorghum with legumes not only produces higher yields per unit area and time, but also provides nutritional security, economic benefits and improves soil health. Sorghum + pigeon pea (2:1/3:1/6:2) and sorghum+ soybean (3:6/2:4) are the two most common intercropping systems. Medium duration sorghum genotypes are most suitable for intercropping. Soybean - rabi sorghum has been found more productive and economically viable system in areas receiving annual rainfall above 700 mm and medium to deep soils having high water retention capacity, and sorghum (kharif)-chickpea, safflower and mustard (rabi) under limited irrigation conditions. Many other millets-based intercrop and sequence cropping are found to be more profitable.

3. New niches of millets cultivation (in rice fallows)

Although millets are known to be climate resilient crops, their cultivation in traditional areas is reducing. New niches like rice fallows sorghum or millets cultivation plays significant role in economic security of the farmers. Sorghum hybrid; CSH 16 (7.50 t ha⁻¹) yielded significantly better than the locally popular hybrid Mahalaxmi 296 (5.86 t ha⁻¹) in rice fallows in Guntur district of Andhra Pradesh, during four years from 2012 to 2016. The significant increase of 27% was observed in grain and ultimately it was resulted into 73% higher monetary benefit to the farmers (**Chapke et al., 2011a**). The district yield average of sorghum is 6.80 t ha⁻¹ during 2014-15 which is around seven times more than the national yield average (0.90 t ha-

1), Such success story can be replicated in the areas where, there is scope in to introduce sorghum and other millets in rice fallows which, assures additional income to the farmers.

4. Millets-based pulses crop systems

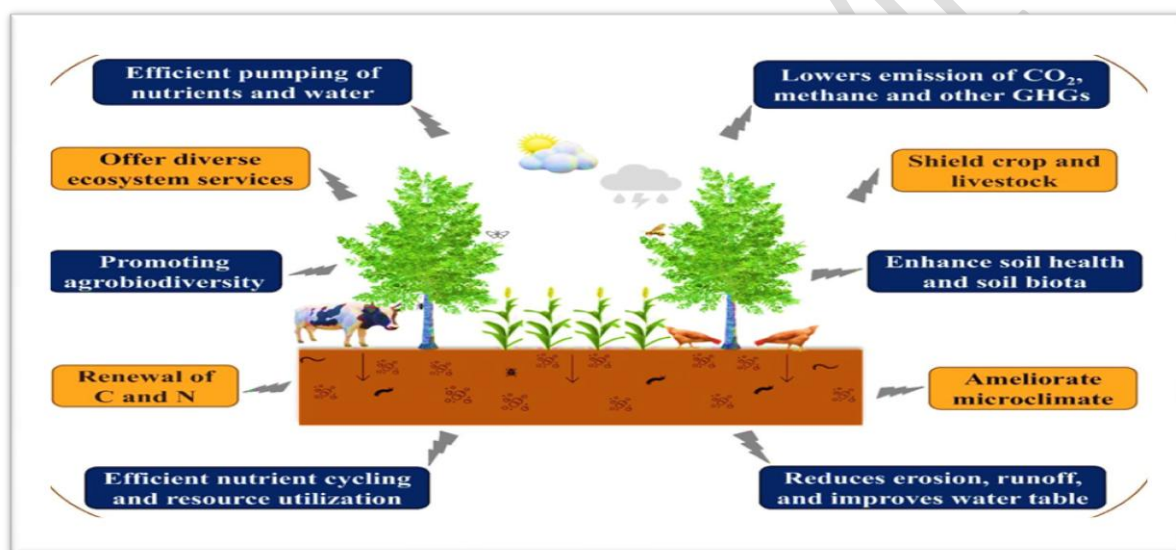
The pulse-based cropping systems are environmentally sustainable also, as they require lower use of fertilizers, pesticides and irrigation in addition to enhancing the productivity of cropping systems by increasing yield of subsequent crops (Reddy 2004, Reddy 2009). To achieve appropriate land use, efficient inter- and sequence-crop systems were recommended based-on soil type, rainfall and length of growing seasons. Intercropping sorghum with legumes not only produces higher yields per unit area and time, but also provides nutritional security, economic benefits and improves soil health. Sorghum+ pigeon pea (2:1/3:1/6:2) and sorghum+ soybean (3:6/2:4) are the two most common intercropping systems. Medium duration sorghum genotypes are most suitable for intercropping. Soybean - rabi sorghum has been found more productive and economically viable system in areas receiving annual rainfall above 700 mm and medium to deep soils having high water retention capacity, and sorghum (kharif)-chickpea, safflower and mustard (rabi) under limited irrigation conditions. Many other millets-based intercrop and sequence cropping are found to be more profitable namely, intercropping of sorghum (CSH 16) with pigeon pea in 2:1/2:2 row ratio and sorghum + soybean in 3:6 row ratio. Medium duration sorghum cultivars like CSH 16, CSH 18, CSH 25, CSV 15 and CSV 20 were most suitable for intercropping with green gram and black gram. Crop sequence with black gram / green gram /soybean / cowpea (fodder) in kharif followed by rabi sorghum, and soybean-rabi sorghum sequential cropping was found more feasible and profitable. Also mix-cropping of sorghum and chickpea is well established and prominent in most of the rainfed areas of the Maharashtra and Karnataka. Promising intercropping with other minor millets were like, Pearl millets + Green gram, Pearl millets + Groundnut, Finger millets + Pigeon pea, FM + Black gram, FM + Field bean, Barnyard millets + Rice bean, Foxtail millets + Pigeon pea, Foxtail millets + Field bean, Kodo millets + Pigeon pea, oilseeds, little millets + Pigeon pea, green gram, Soybean, and Proso millets + Green gram. Crop sequence with Pearl Millets-Chickpea and Finger Millets-Black gram, green gram is also recommended.

Table 6: List of recommended doses for Intercropping systems

Intercropping systems	Recommendation
Sorghum + pigeon pea	Metolachlor 0.75-1.5 kg/Fluchloralin 0.50/Pendimethalin 1.0 /Alachlor at 1.0 kg/ha + 1 inter-row cultivation/h and weeding

Sorghum + cowpea/green gram/black gram	Isoproturon at 0.50 kg/ha or butachlor at 0.75-1.0 kg/ha or metolachlor 1.0 kg + 1 HW
Cropping systems	
Sorghum-cotton	Pre-emergence application of atrazine 0.25 kg/ha in sorghum and pendimethalin 1.0 kg/ha in cotton; Poor establishment of green gram and groundnut after atrazine treated sorghum.
Sorghum-safflower	Pre-emergence application of atrazine at 0.75 kg/ha in sorghum

(Chapke *et al.*, 2018)



(Source: Teli, 2023)

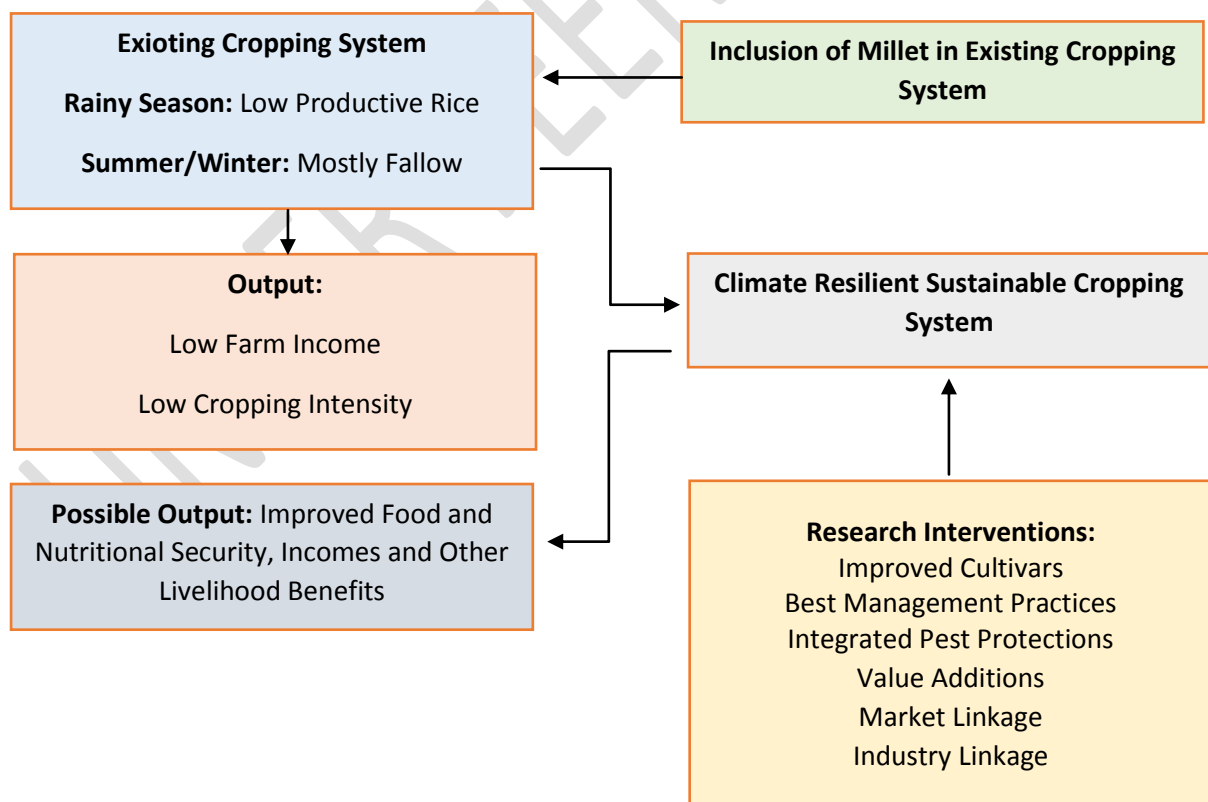
Figure 4. Role of Millet Based IFS in Restoring Agroecology

The combination of millets trees, and livestock restores soil health and renews food security through closed nutrient cycling and effective resource utilization. Integration of trees along with crops can withstand adverse weather conditions (Ali *et al.*, 2019; Bado *et al.*, 2021). Climate change has caused significant challenges in recent years, reducing crop productivity, favouring the spread of weeds, pests, and other diseases, and altering the nutritional value and composition of crops (Adhikari *et al.*, 2015; Rao *et al.*, 2022; Sultan *et al.*, 2013). Thus, there is a need for climate-resilient farming techniques that may increase agricultural output and withstand changing climatic conditions. IFS and millets can both contribute significantly to the provision of numerous agroecosystem services. It can be scaled out even further by combining both crucial components and growing millets under various IFS. The MbIFS can become a climate smart system and a workable option to

address the current challenges of food, nutrition, energy, employment, and environmental security by regulating microclimate, protecting natural resources, and modifying hydrology, biogeochemistry, and agrobiodiversity.

Global Perspective of Millets:

Internationally, the demand for millet based processed products is snowballing day by day. The economic gains through the adoption of millet-based cropping system may be augmented by addressing envisaged benchmarks resulting in significant improvement in productivity, profitability and even export earnings. Millets can be successfully grown in drought prone and unfertile soil where most other crops often failed to grow. Cultivated millets not only contribute to the economic efficiency of farming but also provide food and livelihood security to millions of downtrodden communities of the different parts of the world. Major millets producing counties concentrated in the pockets of southern and western Africa and Asia. Similar growth environment like drought prone and red laterite region of eastern India, predominates in different parts of the Globe like southern and western Africa and Asia west-central High Plains of the USA and western Australia. This millet-based crop production model possibly equally applicable to these regions (Brahmachari *et al.*, 2019).



(Source: Brahmachari *et al.*, 2019)

Figure 5. Strategy to promote millet in existing cropping system

Challenges for Millet:

Despite the breeding efforts, most of breeding programs fail to deliver hybrids due to a vast variation in microclimate (day and night temperature and humidity) and soil apart from rainfall, which requires proper quantification (**Satyavathi et al., 2021**). Further, narrow cultivar diversity in drought-prone ecology also is another factor for this. Thus, there is a high need to give higher priority to the below mentioned areas to promote its production and utilization:

- Development of hybrids/varieties of millet with better regenerative capacity on reversal of dry spell for harsh environment/drought-prone areas (for A1 zone in India).
- Development of hybrids/varieties resistant/tolerant to salt/high temperature.
- Shift in focus of breeding from productivity improvement to the identification of end product-specific traits.
- Mainstreaming of biofortification in millet for iron and zinc.
- Enhancement of shelf life of millet flour and overcome rancidity to promote its products.
- Development of screening protocols and control measures against different diseases such as downy mildew, blast, rust, ergot, smut.
- Generating authentic data on nutritional benefits of millet and bioavailability studies.
- A study on demand survey for millet.

Conclusion and Future Perspectives:

Millet is no more called a coarse cereal rather referred as a nutri-cereal or as a nutraceutical crop and is seen as a potential solution for malnutrition and hidden hunger worldwide. Apart from its excellent nutritional value, its ability to tolerate various abiotic stresses and resist pathogens make it an excellent model for exploring vast genetic and genomic potential of this otherwise important crop and related cereal grasses. These properties thus on the whole make millet an ideal model for studying genomics and a plausible source for gene mining for complex traits (**Gupta et al., 2017**). Molecular biology and biotechnology have proved to be a promising tool for imparting stress tolerance in economically important plants, however, until now the progress is limited among millets mainly due to lack of appropriate genomic resources in these crops. However, with the availability of sorghum, foxtail millet and *Brachypodium* genome sequence, and on-going genomics program in millet and millet will

be of great help for the abiotic and biotic stress tolerance research in these minor cereals. High throughput sequencing platforms will not only be able to overcome the complexity of large and complex millet genome but will also help to understand the regulation of stress tolerance at transcriptional, post-transcriptional and epigenetic levels. An integration of various advanced high throughput omics strategies will definitely revolutionize millet research with the large-scale identification of stress responsive genes/proteins/metabolites that could potentially be used for crop improvement. Potential candidate genes responsible for high yield, biotic and abiotic stress tolerance and those involved in high mineral accumulation isolated from millet can also be utilized for improving other cereal crops through transgenic approaches or genomics assisted breeding and pave way for the development of designer crops for a better and sustainable future. Production of transgenic crops expressing functional foreign genes has to be expanded to millets as well in order to produce transgenic millet varieties expressing foreign genes of agronomic importance, which will be very helpful in improving millet production by conferring resistance to both biotic and abiotic stresses. Development of a super cereal in the future may also be possible by incorporating various agronomically important traits into the genome of a single millet genotype. Thus, utilization of current advances in molecular breeding and genetic engineering together with advanced Omics technologies will definitely prove useful in improving the present scenario of research in millet.

References:

1. Adhikari, U., Nejadhashemi, A. P., & Woznicki, S. A. (2015). Climate change and eastern Africa: a review of impact on major crops. *Food and Energy Security*, 4(2), 110-132.
2. Agriculture Organization of the United Nations. Economic, & Social Department. (2005). *The State of Food Insecurity in the World, 2005: Eradicating World Hunger-Key to Achieving the Millennium Development Goals*. Food & Agriculture Org.
3. Ali, A., & Bhattacharjee, B. (2023). Nutrition security, constraints, and agro-diversification strategies of neglected and underutilized crops to fight global hidden hunger. *Frontiers in Nutrition*, 10, 1144439.
4. Bado, B. V., Whitbread, A., & Manzo, M. L. S. (2021). Improving agricultural productivity using agroforestry systems: Performance of millet, cowpea, and ziziphus-based cropping systems in West Africa Sahel. *Agriculture, Ecosystems & Environment*, 305, 107175.
5. Beddington, J. (2010). Food security: contributions from science to a new and greener revolution. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 365(1537), 61-71.

6. Bhat, S., Nandini, C., & Tippeswamy, V. (2018). Significance of small millets in nutrition and health-A review. *Asian Journal of Dairy and Food Research*, 37(1), 35-40.
7. Bhatt, R., Oliveira, M. W., Verma, K. K., Naresh, R. K., Prasad, S., Majumder, D. Singh, P. K., Kaur, R., Singh, B., & Tripathi, H. (2023). Millets for Global Human Health – A comprehensive review. *Ama, Agricultural Mechanization in Asia, Africa & Latin America*, Volume 54, Issue 04, 12573-12602
8. Brahmachari, K., Sarkar, S., Santra, D. K., & Maitra, S. (2019). Millet for food and nutritional security in drought prone and red laterite region of Eastern India. *International Journal of Plant & Soil Science*, 26(5), 1-7.
9. B Teli, S. (2023). Millet-based agroforestry: a nature-positive farming to achieve climate-resilience and food security in India and Africa.
10. Chapke, R. R., & Tonapi, V. A. (2018). Role of millets in small holder farming system for improved food and nutritional security under changing climate scenario.
11. Chapke, R. R., Mishra, J. S., Subbarayudu, B., Hariprasanna, K., & Patil, J. V. (2011). Sorghum cultivation in rice-fallows: A paradigm shift. *Bulletin, Directorate of Sorghum Research, Hyderabad*, 500(030), 31.
12. Chapke, R. R., Tonapi, V. A., & Ahire, L. (2018). Enhancing farmers' income through pulses in millets-based cropping in rainfed areas. Not Available.
13. Cline, W. R. (2007). *Global warming and agriculture: Impact estimates by country*. Peterson Institute.
14. Dansi, A., Adoukonou-Sagbadja, H., & Vodouhe, R. (2010). Diversity, conservation and related wild species of Fonio millet (*Digitaria* spp.) in the northwest of Benin. *Genetic Resources and Crop Evolution*, 57, 827-839.
15. Food and Agriculture Organization of the United Nations. Technical Note: FAO Methodology to Estimate the Prevalence of Under nourishment; FAO: Rome, Italy; 2012
16. Gupta, S. M., Arora, S., Mirza, N., Pande, A., Lata, C., Puranik, S., ... & Kumar, A. (2017). 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*, 8, 643.
17. Handa, A. K., Dev, I., Rizvi, R. H., Kumar, N., Ram, A., Kumar, D., ... & Rizvi, J. (2019). Successful Agroforestry Models for Different Agro-Ecological Regions in India.
18. Hitu, K. W., M'ribu, K., Liang, H., & Mandelbaum, C. (1997). Fonio millets: ethnobotany, genetic diversity and evolution. *South African Journal of Botany*, 63(4), 185-190.

19. IPCC (2007). "Climate change 2007. The physical science basis," in Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, eds S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, et al. (Cambridge: Cambridge University Press).
20. Lydia Pramitha, J., Ganesan, J., Francis, N., Rajasekharan, R., & Thinakaran, J. (2023). Revitalization of small millets for nutritional and food security by advanced genetics and genomics approaches. *Frontiers in Genetics*, 13, 1007552.
21. Meehl, G. A., Stocker, T. F., Collins, W. D., Friedlingstein, P., Gaye, A. T., Gregory, J. M., et al. (2007). "Global climate projections," in Proceedings of the Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Inter-governmental Panel on Climate Change, eds S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, et al. (Cambridge: Cambridge University Press), 749–844.
22. Naresh, R. K., Bhatt, R., Singh, P. K., Kumar, Y., Tiwari, H., Saini, A., ... & Thakur, H. (2023). Millet: The super food in context of climate change for combating food and water security: A review. *The Pharma Inno*, 12(3), 1040-1049.
23. National Research Council. (1996). Finger millet. *Lost crops of Africa*, 1, 39-57.
24. Newmaster, S. G., Ragupathy, S., Dhivya, S., Jijo, C. J., Sathishkumar, R., and Patel, K. (2013). Chitilappilly Joseph Jijo., Ramalingam Sathishkumar., and Kirit Patel Genomic valorization of the fine scale classification of small millet landraces in southern India. *Genome* 56 (2), 123–127. doi:10.1139/gen-2012-0183
25. Ragupathy, S., Dhivya, S., Patel, K., Sritharan, A., Sambandan, K., Gartaula, H., ... & Newmaster, S. G. (2016). DNA record of some traditional small millet landraces in India and Nepal. *3 Biotech*, 6, 1-19.
26. Rao, C. S., Rakesh, S., Kumar, G. R., Pilli, K., Manasa, R., Sahoo, S., ... & Swamy, G. N. (2022). Technologies, Programs, and Policies for Enhancing Soil Organic Carbon in Rainfed Dryland Ecosystems of India. In *Plans and Policies for Soil Organic Carbon Management in Agriculture* (pp. 27-57). Singapore: Springer Nature Singapore.
27. Rawat, J. M., Pandey, S., Debbarma, P., & Rawat, B. (2021). Preparation of alcoholic beverages by tribal communities in the Indian himalayan region: A review on traditional and ethnic consideration. *Frontiers in Sustainable Food Systems*, 5, 672411.
28. Reddy, A. A. (2004). Consumption pattern, trade and production potential of pulses. *Economic and political weekly*, 4854-4860.
29. Reddy, A. A. (2009). Policy options for India's edible oil complex. *Economic and Political weekly*, 22-24.

30. Sahu, R. K., & Sharma, M. L. (2013). Medicinal and other uses of small millets by the tribal farmers of the Bastar Plateau Zone of Chhattisgarh. *Agriculture Update*, 8(4), 596-599.
31. Satyarathi, K. (Ed.). (2018). *Traditional Foodgrain Crops of Himachal Pradesh*. State Centre on Climate Change & UNEP-GEF-MoEFCC Project, Himachal Pradesh State Biodiversity Board.
32. Satyavathi, C. T., Ambawat, S., Khandelwal, V., & Srivastava, R. K. (2021). Pearl millet: a climate-resilient nutricereal for mitigating hidden hunger and provide nutritional security. *Frontiers in Plant Science*, 12, 659938.
33. Singh, R. P., Qidwai, S., Singh, O., Reddy, B. R., Saharan, S., Kataria, S. K., ... & Kumar, L. (2022). Millets for food and nutritional security in the context of climate resilient agriculture: A Review. *International Journal of Plant & Soil Science*, 939-953.
34. Soam, S. K., Venkatesan, P., Sivaramane, N., Sreekanth, P. D., Rakesh, S., Tamak, J., & Rao, C. S. (2022). Evidence for the economic impacts of Eucalyptus and subabul-based agroforestry in Andhra Pradesh and Telangana. *Ind. J. Agrofor*, 24(2), 52-60.
35. Stireman III, J. O., Dyer, L. A., Janzen, D. H., Singer, M. S., Lill, J. T., Marquis, R. J., ... & Diniz, I. (2005). Climatic unpredictability and parasitism of caterpillars: implications of global warming. *Proceedings of the National Academy of Sciences*, 102(48), 17384-17387.
36. Shukla, A., Lalit, A., Sharma, V., Vats, S., & Alam, A. (2015). Pearl and finger millets: the hope of food security. *Applied Research Journal*, 1(2), 59-66.
37. Sultan, B., Roudier, P., Quirion, P., Alhassane, A., Muller, B., Dingkuhn, M., ... & Baron, C. (2013). Assessing climate change impacts on sorghum and millet yields in the Sudanian and Sahelian savannas of West Africa. *Environmental Research Letters*, 8(1), 014040.
38. Tiwari, H., Naresh, R. K., Bhatt, R., Kumar, Y., Das, D., & Kataria, S. K. (2023a). Underutilized Nutrient Rich Millets: Challenges and Solutions for India's Food and Nutritional Security: A Review. *International Journal of Plant & Soil Science*, 35(2), 45-56.
39. Tiwari, H., Naresh, R. K., Kumar, L., Kataria, S. K., Tewari, S., Saini, A., ... & Asati, R. (2022). Millets for Food and Nutritional Security for Small and Marginal Farmers of North West India in the Context of Climate Change: A Review. *International Journal of Plant & Soil Science*, 34(23), 1694-1705.
40. Tiwari, H., Naresh, R. K., Pandey, M. (2023b). Millets: Key to Food and Nutritional Security in India. *Current Agriculture Trends: e-Newsletter*, 2(2), 1-4.

41. Venkatesan, P., Sundaramari, M., & Venkattakumar, R. (2015). Ethno taxonomical classification of little millet (*Panicum sumatrance*) by the tribal people in Tamilnadu, India.

UNDER PEER REVIEW