



International Journal of Research in Agronomy

E-ISSN: 2618-0618
P-ISSN: 2618-060X
© Agronomy
NAAS Rating (2026): 5.20
www.agronomyjournals.com
2026; 9(7): 1108-1117
Received: 24-04-2026
Accepted: 28-05-2026

Vivek V Kumar
PG Scholar, Department of
Agronomy, College of Agriculture,
Vellayani, Thiruvananthapuram,
Kerala, India

Dr. Jacob John
Professor & Head (Agronomy),
AICRP-IFS, IFSRS, Karamana,
Thiruvananthapuram, Kerala,
India

Dr. Shalin Pillai P
Professor & Head, Department of
Agronomy and Associate Director
of Research, RARS (SZ) College of
Agriculture, Vellayani,
Thiruvananthapuram, Kerala,
India

Dr. Bindhu JS
Associate Professor (Agronomy),
AICRP-IFS, IFSRS, Karamana,
Thiruvananthapuram, Kerala,
India

Dr. Meera AV
Assistant Professor (SS & AC),
AICRP-IFS, IFSRS, Karamana,
Thiruvananthapuram, Kerala,
India

Corresponding Author:
Vivek V Kumar
PG Scholar, Department of
Agronomy, College of Agriculture,
Vellayani, Thiruvananthapuram,
Kerala, India

Performance of sorghum-based cropping systems in tropical environments: A systematic review

Vivek V Kumar, Jacob John, Shalin Pillai P, Bindhu JS and Meera AV

DOI: <https://www.doi.org/10.33545/2618060X.2026.v9.i7n.6066>

Abstract

Sorghum (*Sorghum bicolor* L. Moench) is the fifth-ranked cereal globally, distinguished by its superior tolerance to drought and heat stress, and water use efficiency, making it a critical crop underpinning dietary sustenance across semi-arid tropical regions. This review examines the role of sorghum-based cropping systems in tropical agriculture, covering multiple cropping strategies including intercropping, sequential cropping, rotational cropping, relay cropping, and ratoon cropping. The nutraceutical value of sorghum alongside its inherent agro-climatic adaptability, and global production trends are discussed. Key indices used to evaluate yield advantage such as Sorghum Equivalent Yield, Area Time Equivalent Ratio, and Land Equivalent Ratio, along with economic viability metrics, are reviewed comprehensively from available literature. The paper addresses current challenges including social stigma, limited access to improved varieties, and allelopathic effects, while highlighting priority areas for future research such as germplasm conservation, high-yielding cultivar development, and integrated pest and nutrient management. Sorghum-based intercropping and rotation systems are shown to boost yields, enhance nutritional diversity, reduce chemical inputs, and build climate resilience, aligning with global sustainable agriculture and food security goals.

Keywords: Sorghum, cropping systems, intercropping, tropics, millets, climate resilience, food security

Introduction

As of 2024, global population estimates stand at approximately 8.2 billion (World Bank, 2025) ^[1] and is predicted to reach 9 billion by 2050. Simultaneously, global agricultural land declined to 4.78 billion hectares in 2022, representing a 2 per cent reduction since 2000 (FAO, 2024) ^[2]. Cropland area per person fell significantly from 0.24 hectares in 2000 to 0.20 hectares in 2022 (FAO, 2024) ^[2]. Food and Agriculture Organization (FAO) projections indicate a requirement to scale up global food production by 70 per cent to meet the demands of a growing population, with an even higher increase of nearly 100 per cent required in developing countries (FAO, n.d.) ^[3]. The tropics constitute 36 per cent of Earth's landmass and are home to approximately 43 per cent of the global population as of 2022, including 56 per cent of children under the age of five (National Geographic, 2024) ^[4]. The Human Development Report of 2019 warned that climate change will disproportionately affect tropical developing countries, which have less adaptive capacity than richer counterparts (UNAI, 2022) ^[5]. Against this backdrop, a fundamental shift towards sustainable intensification through climate-resilient cropping systems is imperative (FAO, n.d.) ^[3].

Sorghum (*Sorghum bicolor* L. Moench) is the fifth ranked cereal crop, following wheat, rice, maize, and barley (FAO and ICRISAT, 1996) ^[6]. Widely regarded as the 'camel of crops' owing to its capacity to thrive in arid soils and withstand extended drought periods, sorghum constitutes a vital pillar of food security for millions across the globe (The Crop Trust, n.d.) ^[7]. This review critically synthesizes literature on sorghum-based cropping systems in the tropics, covering classification and nutritional benefits of millets, agronomy and production statistics of sorghum, types of cropping systems, yield and economic performance indices, and key challenges and future research priorities.

Millet

Millet

Millets comprise a diverse group of small-grained cereal crops with a long history of cultivation, serving dual purposes as a staple food for humans and a nutritious fodder source for livestock across the globe. Predominantly grown in the semi-arid tropics of Asia and Africa, developing countries account for 97 per cent of global millet production (Rao *et al.*, 2017) [8]. Due to their exceptional nutrient density and health benefits, millets have been renamed as "nutricereals" (Rasika *et al.*, 2024) [9]. Their capacity to yield satisfactorily within abbreviated growing periods, coupled with superior water-use efficiency and tolerance to infertile soils with minimal nutrient inputs make them uniquely suited to challenging environments (Kole *et al.*, 2015) [10]. Recognizing their importance, the United Nations declared 2023 the International Year of Millets to advance Sustainable Development Goal 2 (Zero Hunger) by promoting millet production and research (Mohanani *et al.*, 2025) [11].

Classification of millets

Millets are categorized into major millets, minor millets, and pseudo-millets based on grain size and botanical classification. Pseudo-millets such as amaranth and buckwheat do not belong to the Poaceae family but are nutritionally comparable and used similarly (Mohanani *et al.*, 2025) [11]. They are an excellent source of health-boosting proteins with a well-rounded amino acid profile, along with phytochemicals, dietary fibres, vitamins, and minerals (Sharma *et al.*, 2023) [12]. The classification, origin, common names, and uses of various millets are presented in Table 1.

Table 1: Classification of millets, their origin, common names, and uses

Millet	Origin	Common names	Uses
Major millets			
Sorghum (<i>Sorghum bicolor</i>)	NE central Africa	Jowar, juar, cholam, great millet	Kafrin protein indigestibility beneficial for hyperglycaemia patients
Pearl millet (<i>Pennisetum glaucum</i>)	Western Africa	Bajra, cumbu, bulrush	Highest source of niacin among cereals
Finger millet (<i>Eleusine coracana</i>)	Eastern Africa	Ragi, keppai	Richest cereal source of calcium
Minor millets			
Fox tail millet (<i>Setaria italica</i>)	China	Tenai, kakum, thinai	Most digestible and non-allergic grain
Proso millet (<i>Panicum milliaceum</i>)	NE China	Pani varagu, chena, variga	Reduces cholesterol and heart disease risk
Little millet (<i>Panicum sumatrense</i>)	Eastern Ghats of India	Samai, kutki	High antioxidant activities
Kodo millet (<i>Paspalum scrobiculatum</i>)	India	Varagu, kodon	Excellent for nervous system strengthening
Barnyard millet (<i>Echinochola crusgalli</i>)	Japan	Kuthiravolly, sanwa	Antioxidant and blood lipid reducing properties
Teff (<i>Eragrostis tef</i>)	Ethiopia	Abyssinian lovegrass	Staple food of Ethiopia; grows in waterlogged and drought conditions
Browntop millet (<i>Brachiaria ramosa</i>)	Japan and India	Kula samai	Grows in less fertile sandy loam soil; least expensive
Fonio (<i>Digitaria exilis</i>)	West Africa	Hungry rice	Rich in methionine; prevents and manages diabetes
Pseudo millets			
Amaranth (<i>Amaranthus sp.</i>)	Central America	Keerai vidai, ramdana	Contains lunasin with cancer-preventive and antihypertensive properties
Buckwheat (<i>Fagopyrum esculentum</i>)	SW China	Kuttu	Contains rutin; anti-inflammatory and anticarcinogenic properties

Source: Mohanani *et al.* (2025) [11]; Verma and Khurana (2020) [13]; Bhat *et al.* (2018) [14]

Climate resilient properties of millets

In an agricultural context, climate resilience denotes the inherent ability of a farming system to sustain its core productive functions and structural integrity under conditions of climatic uncertainty and weather-related perturbations (Eeswaran *et al.*, 2021) [15]. The C4 photosynthetic mechanism, common to all millet species, suppresses photorespiratory losses and substantially elevates the efficiency of water use, enabling them to flourish in warm, dry climates (Wilson and VanBuren, 2022) [16]. Compared to major cereals, sorghum and millet have significantly smaller carbon footprints (878 kg C ha⁻¹) versus wheat (1000 kg C ha⁻¹), rice (956 kg C ha⁻¹), and maize (935 kg C ha⁻¹) (Debangshi, 2022; Ishaq *et al.*, 2025) [17, 18]. Water requirements and water use efficiency data for millets compared to other cereals are presented in Table 2.

Table 2: Water requirement of millets compared to other cereals

Crop	Water requirement (mm)	Growing period (days)	WUE (kg ha ⁻¹ mm ⁻¹)
Rice	1200-1400	120-150	2-4
Maize	500-800	95-110	4-6
Sorghum	450-650	100-140	5-8
Pearl millet	200-300	60-70	8-10
Wheat	450-650	120-150	4-6

Source: Mishra *et al.* (2024) [19]

Sorghum

Sorghum ranks among the world's most strategically important food crops, occupying the fifth position in global cereal production (FAO and ICRISAT, 1996) [6]. Anthropological evidence indicates that sorghum in its wild form was already familiar to early hunter-gatherer societies as far back as 8000 BC. Its systematic cultivation is traced to the Eastern Sudanese savannah around 4000 BC, from where it gradually diffused across more than 100 nations and today constitutes over 60 per cent of total global millet output (Mohanani *et al.*, 2025; Bhat *et al.*, 2018) [11, 14]. The exceptional drought tolerance of sorghum stems from a combination of morphological and physiological adaptations, notably its extensive deep-penetrating root architecture, wax-coated leaf surfaces, and specialized mortar cells within the stem, together with its C4 metabolic pathway, these attributes enable efficient water conservation and facilitate access to subsurface soil moisture reserves (Ishaq *et al.*, 2025) [18]. C4 plants like sorghum have 50 per cent higher Radiation Use Efficiency (RUE) than C3 crops such as rice (Kajala *et al.*, 2011) [20]. Cultivated sorghum is categorized into four primary groups: grain sorghum, forage sorghum, grass sorghum, and Sudan sorghum, based on pericarp colour, endosperm type, and other morphological traits (Macrae *et al.*, 1993) [21].

Nutrient composition of sorghum

On a per 100 g basis, sorghum grain presents a proximate composition of approximately 11.9 per cent moisture, 10.4 per cent protein, 1.9 per cent fat, and 72.6 per cent carbohydrates, collectively yielding an energy value of around 349 kcal (Gopalan *et al.*, 1996) ^[22]. Starch constitutes the predominant carbohydrate fraction of sorghum, with amylose accounting for approximately 21.28 per cent of the starch component, and total dietary fibre representing 14.3 per cent of grain composition (Hosmani and Chittapur, 1997) ^[23]. Sorghum contains a notable amount of Slow Digestible Starch (SDS), which prolongs carbohydrate digestion and absorption, making it particularly favourable for individuals with metabolic disorders such as diabetes and hyperlipidaemia (Rao *et al.*, 2017) ^[8]. Protein distribution within the sorghum grain is highly compartmentalized, around 80 per cent of total grain nitrogen is concentrated in the endosperm, largely in the form of prolamin proteins known as kafirins, whereas the germ fraction harbours albumins and globulins that are particularly distinguished by their relatively high lysine content (Taylor and Schussler, 1986) ^[24]. Nutrient composition of sorghum compared with other major cereals is presented in Table 3.

Table 3: Nutrient composition of sorghum compared with maize, rice and wheat (per 100 g)

Content	Sorghum	Dry maize	Raw rice	Whole wheat
Protein (g)	9.97±0.43	8.80±0.49	7.94±0.58	0.59±0.60
Ash (g)	1.39±0.34	1.17±0.16	0.56±0.08	1.42±0.19
Total fat (g)	1.73±0.31	3.77±0.48	0.52±0.05	1.47±0.05
Total Dietary Fibre (g)	10.22±0.49	12.24±0.93	2.81±0.42	11.23±0.77
Calcium (mg)	27.60±3.71	8.91±0.61	10.93±1.79	39.36±5.65
Magnesium (mg)	133±14.8	145±12.4	93.91±9.11	125±11.5
Phosphorus (mg)	274±35.7	279±35.3	267±64.9	315±41.8
Zinc (mg)	1.96±0.31	2.27±0.23	1.68±0.33	2.85±0.65
Iron (mg)	3.95±0.94	2.49±0.32	1.02±0.35	3.97±0.78
Carbohydrates (g)	67.68±1.03	64.77±1.58	78.24±1.07	64.72±1.74
Energy (KJ)	1398±13	1398±25	1491±15	1347±23

Source: Longvah *et al.* (2017) ^[25]

Health benefits of sorghum

Studies have confirmed that sorghum products are non-toxic to individuals with celiac disease (Ciaccia *et al.*, 2007) ^[26]. Its abundant dietary fibre helps satisfy hunger and reduces the risk of obesity-related conditions including diabetes and cardiovascular diseases (Rao *et al.*, 2017) ^[8]. A study conducted by the National Institute of Nutrition (ICMR) in 2010, as reported by Thakur *et al.* (2023) ^[27], established that sorghum-based food preparations exhibit a low Glycaemic Index (GI), which attenuates the glycaemic response following food intake. Sorghum also possesses anti-mutagenic and anti-cancer properties attributed to its polyphenol and tannin content (Vijayreddy and Reddy, 2023) ^[28]. Furthermore, the considerable antioxidant potential of sorghum enables it to neutralize harmful free radicals that contribute to oxidative stress, a key driver in the pathogenesis of neurodegenerative and cardiovascular conditions including Alzheimer’s disease, atherosclerosis, myocardial infarction, and Parkinson’s disease (Rao *et al.*, 2017) ^[8].

Processing of sorghum

Sorghum for human consumption undergoes primary processing (dehulling/pearling, milling into flour and semolina) and secondary processing (flaking, extrusion, popping, baking, and blending) (FAO, 1999; Rao *et al.*, 2017) ^[29, 8]. Beyond food, sorghum has broad industrial applications in health,

pharmaceutical, packaging, and bio-industrial sectors. The grain fraction is particularly valued as a source of health-promoting bioactive compounds, encompassing phenolic antioxidants, wax constituents with cholesterol-modulating properties, and a broad array of phytochemicals with established nutraceutical significance (Aruna and Visarada, 2019) ^[30].

Area and production of sorghum

Globally, sorghum production reached 62.36 million tons during 2024-25. The United States leads with 8.73 million tons (14 per cent), followed by Nigeria with 6.5 million tons (10 per cent), India with 6.0 million tons (9.6 per cent), and Brazil with 5 million tons (8 per cent) (USDA, 2025a) ^[31]. While over 110 countries cultivate sorghum, just ten nations account for more than one million hectares each, collectively producing over 68 per cent of the world’s total sorghum (Charyulu *et al.*, 2024) ^[32]. Top producing countries are listed in Table 4.

Table 4: Top ten sorghum producing countries (2024-2025)

Country	% of total production	Total production (2024-25, MT)
United States	14	8.73 million
Nigeria	10	6.5 million
India	10	6 million
Brazil	8	5 million
Mexico	7	4.2 million
Ethiopia	7	4.1 million
Argentina	6	3.5 million
Sudan	5	3.3 million
China	5	3 million
Australia	4	2.33 million

Source: USDA (2025a) ^[31]

Over the last decade, the global area under sorghum cultivation slightly decreased from 41.79 million hectares in 2011-2013 to 39.9 million hectares. Despite this, global production remained relatively stable due to increased productivity in various regions. Africa leads, accounting for 46 per cent of global production, with the Americas at 35 per cent (Charyulu *et al.*, 2024) ^[32]. Within India, sorghum occupies approximately 4.8 million hectares, sustaining a steady yield of 1.25 t ha⁻¹. The rabi cropping season dominates national production, accounting for 53 per cent of total output. State-wise, Maharashtra emerges as the leading producer with a 37 per cent share, trailed by Karnataka and Tamil Nadu at 22 and 10 per cent, respectively (USDA, 2025b) ^[33].

Cropping system and global trends

A cropping system is broadly defined as the organised pattern of crop cultivation on a given farm unit, encompassing the interplay between crop arrangements, available natural resources, farm management practices, and applicable technologies (Reddy and Reddy, 2023) ^[34]. The practice of cultivating multiple crops sequentially or as mixed crops dates back to ancient times, as evidenced by references in the Vedas to double cropping, "Purvaha" for the initial crop and "Aparvaha" for the later one (Palaniappan and Sivaraman, 2006) ^[35]. Current estimates indicate that multiple cropping is practised on approximately 134.4 million hectares, equivalent to 12 per cent of total global cropland, of which irrigated lands contribute a disproportionately large share of 40 per cent. Among the various forms of multiple cropping, double cropping is by far the most widespread, extending across 130.4 mha or 11.3 per cent of global cropland (Portmann *et al.*, 2010; Siebert *et al.*, 2010; Waha *et al.*, 2020) ^[36, 37, 38]. Top global multiple cropping systems are listed in Table 5.

Table 5: Top five global multiple cropping systems by physical area

Cropping system	Irrigation status	Physical area (mha)
Rice-Rice	Irrigated	32.66
Wheat-Rice	Irrigated	14.38
Wheat-Maize	Irrigated	12.16
Wheat-Cotton	Irrigated	4.3
Rapeseed-annual crop	Rainfed	3.56

Source: Waha *et al.* (2020) ^[38]

Cropping systems in tropics

In traditional tropical agricultural systems, multiple cropping became essential due to the scarcity of arable land (Palaniappan and Sivaraman, 2006) ^[35]. In tropical Asia, rice-based cropping systems dominate coastal deltas, though large areas remain fallow during the dry season due to salinity and insufficient freshwater (Johnson and Humphreys, 2021) ^[39]. In Africa, multiple cropping systems revolve around maize, wheat, or millet, with sorghum featuring prominently during the long rainy season (Waha *et al.*, 2020) ^[38]. In Brazil, soybean as the primary crop followed by a "safrinha" minor crop such as maize, cotton, or millet forms typical double-cropping systems (Anderson *et al.*, 2017) ^[40]. The most important crops in global multiple cropping systems are presented in Table 6.

Table 6: Most used crops in multiple cropping systems globally

Crop	% under multiple cropping	Area (mha)
Rice	44	49.63
Wheat	13	24.12
Maize	10	13.49

Source: Waha *et al.* (2020) ^[38]

Sorghum as a component for cropping systems in tropics

Sorghum plays a key role in rainfed cropping systems. Its wide row spacing (45 cm) and relatively short maturity (90-120 days) create excellent opportunities for intercropping, allowing efficient use of natural resources (Prasad, 2022) ^[41]. The C4 photosynthetic pathway enables a high crop growth rate, suggesting that the best use of resources occurs when the peak growth phases of sorghum and companion crops do not overlap (ICRISAT, 1981) ^[42]. In areas with inadequate rainfall, forage sorghum serves as an effective substitute for maize (Ji *et al.*, 2025) ^[43]. In Central and Northern Ethiopia, farmers cultivate maize, wheat, and sorghum during the primary rainy season (kiremt, June-September), and a second crop during the shorter belg season (March-May) if rainfall is sufficient (Kassie *et al.*, 2013) ^[44].

Monocropping of sorghum

Monocropping or monoculture refers to a farming practice in which a single crop species is exclusively grown on a given piece of land during a cropping season (Reddy and Reddy, 2023) ^[34]. In West Africa, particularly in Sahelian regions receiving between 400 and 600 mm of rainfall, sorghum is commonly grown as a monocrop (ICRISAT, 1981) ^[42]. However, growing sorghum and maize together as an intercrop has been shown to be more profitable than growing either crop alone in monoculture (Clara *et al.*, n.d.) ^[45].

Multiple cropping of sorghum

Growing two or more crops on the same piece of land in a single

calendar year is known as multiple cropping (Reddy and Reddy, 2023) ^[34]. Sorghum is cultivated using several multiple cropping strategies, including intercropping, sequential cropping, rotational cropping, relay cropping, and ratoon cropping (ICRISAT, 1981) ^[42]. A study conducted in Nigeria by Onuwa (2023) ^[46] revealed that 98.2 per cent of sorghum farmers adopted mixed cropping as a mitigation measure for production risks, promoting agro-crop diversity in smallholder farming systems.

Sequential cropping of sorghum

Sequential cropping involves growing two or three crops successively on the same land, with each crop planted only after the previous one has been harvested (Magnolo *et al.*, 2021) ^[47]. In coastal districts of Andhra Pradesh, sorghum is cultivated in rice-fallows during late-rabi due to insufficient water for a second rice crop (Prasad, 2022) ^[41]. Key strategies to minimize water stress include early planting to leverage pre-season rains, minimizing the gap between crops, and maximizing use of post-season soil moisture (Radulovich, 2000) ^[48].

Relay cropping involves planting a new crop in the same field before the previous crop is harvested, shortening the total growing period (Reddy and Reddy, 2023) ^[34]. ICRISAT (1981) ^[42] demonstrated that relay cropping of sorghum led to a higher success rate compared to sequential cropping of 105-day sorghum varieties and also showed a reduced likelihood of a wet week at harvest. Relay cropping has also been shown to reduce Striga infestation by 27.4-38.7 per cent (Reda *et al.*, 2005) ^[49], though challenges include difficulty of sowing into an established crop and the risk of damaging relay crop seedlings during harvest.

Ratooning involves growing a new crop from the regrowth of roots or stalks of a previously harvested crop. Ratooning of sorghum from its original stubble provides higher resource use efficiency and economic benefit compared to direct-sown crops (Zhou *et al.*, 2022) ^[50]. The ratoon crop starts and matures faster, offering a shorter overall growing period. One well-known multi-cut fodder sorghum variety exploiting this is Meethi Sudan (SSG 59-3) in India (Meena and Sihag, 2024) ^[51]. A primary drawback is that the ratoon crop typically yields 50-65 per cent less than a freshly sown crop, attributable to lower chlorophyll content (SPAD values), reduced Leaf Area Index (LAI), and diminished Total Dry Weight (TDW) (ICRISAT, 1981; Zhou *et al.*, 2022) ^[42, 50].

Rotational cropping of sorghum

Crop rotation constitutes a long-term agricultural strategy characterised by a planned and recurring sequence of different crop species on the same piece of land across successive growing seasons. Its foremost agronomic benefit lies in interrupting the proliferation of crop-specific pests by depriving them of their preferred host plants (Reddy and Reddy, 2023). The sorghum-tef-wheat/barley rotation is prevalent in Ethiopia, strategically designed to optimize nutrient and water uptake at various soil depths, given that sorghum's deep root system accesses water and nutrients that have penetrated deeper soil layers during the preceding season (Shimelis *et al.*, 2016) ^[52]. Fusarium wilt in pigeon pea can also be reduced by rotating with sorghum (Meena and Sihag, 2024) ^[51]. Yield advantages of crops following sorghum in rotation are presented in Table 7.

Table 7: Yield advantage of crops under sorghum-based crop rotation

Crop following sorghum	Yield increase (%)	Primary benefit/Mechanism
Cotton	26	Breaks soil disease cycles (e.g., verticillium wilt); increased soil moisture storage; wind protection from residue
Soybean	16.6	Enhanced soil fertility; improved soil physical characteristics; superior weed management; decreased incidence of diseases, nematodes, and insect pests
Corn	8.4	Larger root biomass leaving more organic material; helps break disease and pest cycles

Source: Bean (2023) [53]

A key disadvantage of sorghum in crop rotation is its potential depressive effect on subsequent crops due to sorghum's considerably high uptake of soil nutrients and moisture, along with the temporary unavailability of nitrogen caused by microbial decomposition of its residue-rich straw, which has a notably wide carbon-to-nitrogen ratio of 80:1 (ICRISAT, 1981; Meena and Sihag, 2024) [42, 51]. Sorghum also releases allelopathic phenolic compounds including Dhurrin, sorgoleone, p-coumaric acid, and ferulic acid, which can inhibit subsequent crop growth and suppress weed germination (Hussain *et al.*, 2021; Ullah *et al.*, 2022) [54, 55]. However, properly incorporated sorghum residue can offer dual benefits of improved weed management and enhanced nitrogen release, with mung bean yields increasing by over 37 per cent in Faisalabad (Ullah *et al.*, 2022) [55].

Intercropping of sorghum

Intercropping refers to the concurrent cultivation of two or more crop species within the same field during the same growing season, arranged according to a defined spatial pattern (Reddy and Reddy, 2023) [34]. Complementary use of nutrients, water, and sunlight by component crops contributes to higher yields compared to sole cropping (ICRISAT, 1981) [42]. Well-planned

intercropping systems offer efficient resource use, increased biodiversity, improved pest management, enhanced soil fertility, and reduced dependence on off-farm inputs (Glaze-Corcoran *et al.*, 2020) [56].

Intercropping sorghum with legumes significantly boosts grain yield: cowpea (fodder) at 34 per cent, cowpea (grain) at 27 per cent, greengram at 20 per cent, blackgram at 17 per cent, groundnut at 12 per cent, and soybean at 8 per cent compared to sole cropping (Prasad, 2022) [41]. Intercropping groundnut with sorghum can reduce groundnut rust and bud necrosis, while Striga infestation in sorghum can be controlled by intercropping with groundnut, soybean, or cowpea (Meena and Sihag, 2024) [51]. An improved sorghum/pigeonpea intercropping system where pigeonpea is planted in every third row demonstrated near-full sorghum yield (4240 kg ha⁻¹ versus 4500 kg ha⁻¹ in sole crop) while pigeonpea yielded 53 per cent of its sole-crop dry matter (ICRISAT, 1981) [42]. Among the various sorghum-based cropping arrangements, intercropping with pigeonpea consistently demonstrates a higher probability of success than either sequential or relay cropping systems, owing to its lower dependence on a second well-defined rainfall spell for establishment (Fig. 1) (ICRISAT, 1981) [42].

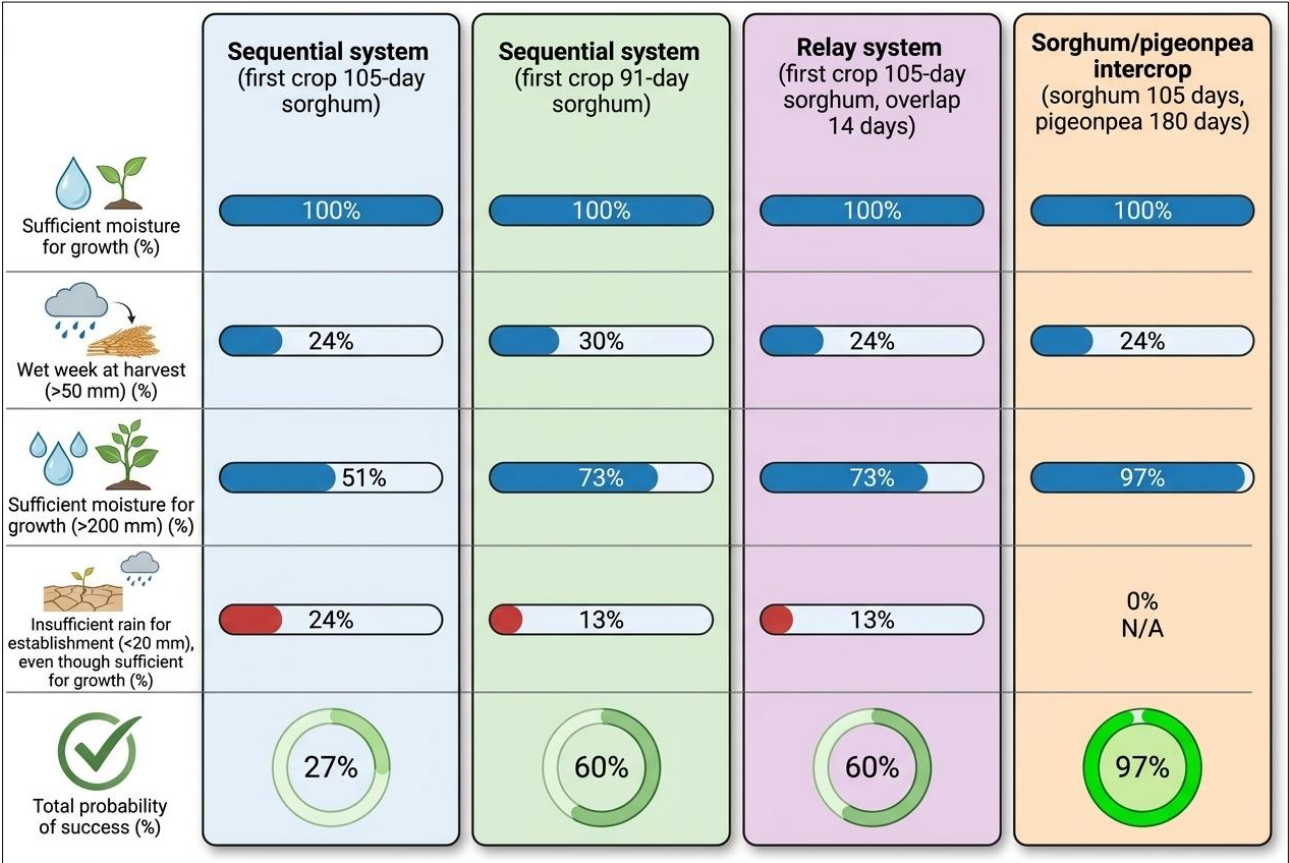


Fig 1: Comparative success rate (%) of sequential cropping, relay cropping and intercropping of sorghum (redrawn from ICRISAT, 1981) [42]

Indices to assess yield advantage**Sorghum Equivalent Yield (SEY)**

The yields of different crops are converted into equivalent yield of sorghum based on market price of the produce (Francis, 1986; Singh and Arya, 2020) ^[57, 58]:

SEY = Sorghum grain yield (kg ha⁻¹) + [Grain yield of intercrop (kg ha⁻¹) x Price kg⁻¹ of intercrop / Price kg⁻¹ of sorghum grain]
SEY values of sorghum-based cropping systems are presented in Table 8.

Table 8: Sorghum Equivalent Yield (SEY) of sorghum-based cropping systems

Cropping system	Ratio	SEY (t ha ⁻¹)	Reference
Sorghum + pigeonpea	2:1	6.5	ICAR-IIMR (n.d.) ^[59]
Sorghum + soybean	1:2	5.34	Prasad (2022) ^[41]
Sorghum + soybean	2:1	4.92	Prasad (2022) ^[41]
Sorghum + soybean	2:4	4.79	Prasad (2022) ^[41]
Sorghum + groundnut	1:2	8.9	Prasad (2022) ^[41]
Sorghum + groundnut	2:1	5.2	Prasad (2022) ^[41]
Sorghum + blackgram	1:1	3.4	Sujathamma and Nedunchezhiyan (2022) ^[60]
Sorghum + blackgram	2:2	3.62	Sujathamma and Nedunchezhiyan (2022) ^[60]
Sorghum + greengram	1:1	2.87	Sujathamma and Nedunchezhiyan (2022) ^[60]
Sorghum + greengram	2:2	2.74	Sujathamma and Nedunchezhiyan (2022) ^[60]
Sorghum + chickpea	1:1	2.55	Sujathamma and Nedunchezhiyan (2022) ^[60]
Sorghum + chickpea	2:2	2.56	Sujathamma and Nedunchezhiyan (2022) ^[60]

Land Equivalent Ratio (LER)

The Land Equivalent Ratio (LER) is a widely used intercropping efficiency index that quantifies the relative land area required under sole cropping to achieve the same total yield as that obtained from a unit area of intercropping, under equivalent management conditions. It is derived by summing the partial LERs of each component crop, where each partial LER is the ratio of the intercrop yield to the corresponding sole crop yield (FAO, 1985) ^[61]. If LER > 1, intercropping is advantageous; if LER = 1,

no profit or loss; if LER < 1, intercropping is disadvantageous (Meena and Sihag, 2024) ^[51].

$$LER = (Y_{ab}/Y_{aa}) + (Y_{ba}/Y_{bb})$$

Where: Y_{ab} and Y_{ba} = individual yield of crops in intercropping; Y_{aa} and Y_{bb} = their yield as sole crops

LER values for sorghum-based cropping systems are presented in Table 9.

Table 9: Land Equivalent Ratio (LER) of sorghum-based cropping systems

Cropping system	Ratio	LER	Reference
Sorghum + blackgram	1:1	1.29	Sujathamma and Nedunchezhiyan (2022) ^[60]
Sorghum + blackgram	2:2	1.31	Sujathamma and Nedunchezhiyan (2022) ^[60]
Sorghum + greengram	1:1	1.14	Sujathamma and Nedunchezhiyan (2022) ^[60]
Sorghum + greengram	2:2	1.36	Sujathamma and Nedunchezhiyan (2022) ^[60]
Sorghum + chickpea	1:1	1.40	Sujathamma and Nedunchezhiyan (2022) ^[60]
Sorghum + chickpea	2:2	1.52	Sujathamma and Nedunchezhiyan (2022) ^[60]
Sorghum + cowpea	1:1	1.29	Chaudhary <i>et al.</i> (2020) ^[62]
Sorghum + cowpea	1:2	1.26	Chaudhary <i>et al.</i> (2020) ^[62]
Sorghum + cowpea	2:1	1.30	Chaudhary <i>et al.</i> (2020) ^[62]
Sorghum + groundnut	1:1	1.22	Nagla <i>et al.</i> (2022) ^[63]
Sorghum + groundnut	1:2	1.01	Nagla <i>et al.</i> (2022) ^[63]
Sorghum + groundnut	2:1	1.01	Nagla <i>et al.</i> (2022) ^[63]
Sorghum + groundnut	2:2	1.35	Nagla <i>et al.</i> (2022) ^[63]
Fodder sorghum + pigeonpea	2:1	1.58	Verma <i>et al.</i> (2005) ^[64]
Fodder sorghum + pigeonpea	1:1	1.41	Verma <i>et al.</i> (2005) ^[64]
Fodder sorghum + pigeonpea	3:1	1.41	Verma <i>et al.</i> (2005) ^[64]

Area Time Equivalent Ratio (ATER)

The ATER addresses a conceptual limitation of LER by accounting for the duration of the cropping system, since intercrops often occupy land longer than individual component species (Hiebsch and McCollum, 1987) ^[65]:

ATER = [LER of main crop x duration of main crop + LER of intercrop x duration of intercrop] / Total duration of intercropping system

ATER values for sorghum-based cropping systems are presented in Table 10.

Table 10: Area Time Equivalent Ratio (ATER) of sorghum-based cropping systems

Cropping system	Ratio	ATER	Reference
Sorghum + blackgram	1:1	1.26	Sujathamma and Nedunchezhiyan (2022) ^[60]
Sorghum + blackgram	2:2	1.27	Sujathamma and Nedunchezhiyan (2022) ^[60]
Sorghum + greengram	1:1	1.03	Sujathamma and Nedunchezhiyan (2022) ^[60]
Sorghum + greengram	2:2	1.19	Sujathamma and Nedunchezhiyan (2022) ^[60]
Sorghum + chickpea	1:1	1.35	Sujathamma and Nedunchezhiyan (2022) ^[60]
Sorghum + chickpea	2:2	1.47	Sujathamma and Nedunchezhiyan (2022) ^[60]
Fodder sorghum + pigeonpea	2:1	1.21	Verma <i>et al.</i> (2005) ^[64]
Fodder sorghum + pigeonpea	1:1	1.12	Verma <i>et al.</i> (2005) ^[64]
Fodder sorghum + pigeonpea	3:1	0.91	Verma <i>et al.</i> (2005) ^[64]

Indices to assess economic viability

Net Returns

Net returns are calculated by subtracting the total cost of

cultivation from gross returns, giving the actual profit from the system. Net returns of sorghum-based intercropping systems are presented in Table 11.

Table 11: Net returns of sorghum-based intercropping systems

Cropping system	Ratio	Net returns (x10 ³ Rs. ha ⁻¹)	Reference
Sorghum + blackgram	1:1	43.142	Sujathamma and Nedunchezhiyan (2022) ^[60]
Sorghum + blackgram	2:2	45.645	Sujathamma and Nedunchezhiyan (2022) ^[60]
Sorghum + greengram	1:1	37.834	Sujathamma and Nedunchezhiyan (2022) ^[60]
Sorghum + greengram	2:2	25.122	Sujathamma and Nedunchezhiyan (2022) ^[60]
Sorghum + chickpea	1:1	19.973	Sujathamma and Nedunchezhiyan (2022) ^[60]
Sorghum + chickpea	2:2	19.824	Sujathamma and Nedunchezhiyan (2022) ^[60]
Fodder sorghum + pigeonpea	2:1	30.179	Verma <i>et al.</i> (2005) ^[64]
Fodder sorghum + pigeonpea	1:1	27.008	Verma <i>et al.</i> (2005) ^[64]
Fodder sorghum + pigeonpea	3:1	27.687	Verma <i>et al.</i> (2005) ^[64]
Sorghum + lablab	2:2	56.431	Darshini <i>et al.</i> (2024) ^[66]
Sorghum + lablab	2:1	67.872	Darshini <i>et al.</i> (2024) ^[66]

Benefit-Cost Ratio (B:C)

The B:C ratio provides an estimate of the benefit derived relative to expenditure incurred. A ratio greater than 1 indicates economic viability of the cropping system. Table 12 presents the Benefit-cost ratios of various sorghum-based cropping systems.

Table 12: Benefit-cost ratio of sorghum-based cropping systems.

Cropping system	Ratio	B:C ratio	Reference
Fodder sorghum + pigeonpea	2:1	4.96	Verma <i>et al.</i> (2005) ^[64]
Fodder sorghum + pigeonpea	1:1	4.57	Verma <i>et al.</i> (2005) ^[64]
Fodder sorghum + pigeonpea	3:1	4.68	Verma <i>et al.</i> (2005) ^[64]
Sorghum + lablab	2:2	1.9	Darshini <i>et al.</i> (2024) ^[66]
Sorghum + lablab	2:1	2.7	Darshini <i>et al.</i> (2024) ^[66]
Sorghum + greengram	2:1	2.7	Darshini <i>et al.</i> (2024) ^[66]
Sorghum + greengram	2:2	2.6	Darshini <i>et al.</i> (2024) ^[66]
Sorghum + cowpea	2:1	2.1	Darshini <i>et al.</i> (2024) ^[66]
Sorghum + cowpea	2:2	2.4	Darshini <i>et al.</i> (2024)

Effect of intercropping on growth parameters

Intercropping sorghum with cowpea resulted in markedly superior agronomic performance relative to sole sorghum and sorghum intercropped with clusterbean, as evidenced by improvements in leaf area index, leaf-to-stem ratio, forage and crude protein yields, and crop nitrogen uptake (Ram and Singh, 2002) ^[67]. Chaudhary *et al.* (2020) ^[62] reported that plant height in sole sorghum was 285.3 cm and in sole cowpea was 194.1 cm.

In intercropping systems, sorghum height ranged from 287.7 cm (2:1 ratio) to 293.1 cm (1:2 ratio), while cowpea height ranged from 174.9 cm to 186.8 cm across ratios. The LAI for sole sorghum was 4.87 and for sole cowpea was 4.09, with corresponding intercrop ratios (1:1, 1:2, 2:1, 2:2) yielding LAI values of 4.91, 4.52, 4.68, and 4.21 respectively.

The enhanced productivity observed in the intercropping treatments was attributed to a constellation of growth-promoting factors, including taller plant stature, proliferation of leaf number, greater leaf area development, and accelerated dry matter production, processes substantially facilitated by the biological nitrogen contribution of the cowpea component (Ram and Singh, 2002) ^[67]. The highest total green biomass (49,099 kg ha⁻¹) and dry biomass (10,330 kg ha⁻¹) were obtained from the 2:1 sorghum: cowpea intercropping ratio (Chaudhary *et al.*, 2020) ^[62].

Benefits of sorghum-based cropping systems

Sorghum's adaptability to diverse agro-ecologies including dry, hot, semi-arid, and tropical areas makes it widely grown even with limited water and poor soil (ICRISAT, n.d.) ^[42]. Being naturally gluten-free, sorghum serves as a primary food source for populations in regions of semi-arid tropics, including celiac patients (Reddy *et al.*, 2022) ^[68]. Its remarkable versatility across four categories (grain, sweet, forage, and biomass sorghum) each with distinct genetic characteristics and applications, is highlighted in Table 13.

Table 13: Characteristics and uses of sorghum groups

Sorghum group	Height (m)	Traits	Uses
Forage sorghum	1.8-3.6	Single/multi-cut harvest; high digestibility and palatability	Livestock feed
Sweet sorghum	>3	Abundance of extractable sugars localized within the stem tissue	High-sugar forage; syrup production biofuel production;
Grain sorghum	0.6-1.2	High grain yield	Staple food; biofuel; livestock feed
Biomass sorghum	3.5-6	High lignocellulosic biomass; photoperiod-sensitive; dual-purpose	Biomaterial production; biofuel; biogas

Source: Tanwar *et al.* (2023) ^[69]

Intercropping sorghum with legumes improves water use efficiency (WUE) by providing more extensive soil cover that reduces evaporation, and their varied root depths allow absorption of moisture from different soil layers (Duvvada and Maitra, 2020) ^[70]. Intercropping sorghum with cowpea and bottle gourd notably enhanced WUE by 54.65 per cent and 46.98 per cent respectively, compared to sole cropping (Duvvada and Maitra, 2020) ^[70].

Challenges in sorghum cropping systems: A significant socio-

cultural challenge is the social stigma labelling sorghum as a "poor man's crop," which leads farmers to prefer maize despite sorghum's substantially lower water requirements (Hadebe *et al.*, 2017) ^[71]. Limited access to improved varieties, despite sorghum's recognized priority status, is reflected in insufficient investment in improved inputs. The practice of using previous season's grain as seed results in quality degradation during storage (Dunjana *et al.*, 2022) ^[72]. The lack of high-yielding productive cultivars and difficulty in standardizing nutrient requirements in complex

cropping systems are additional agronomic constraints (Harish *et al.*, 2024) ^[73]. Furthermore, a recent study in Senegal by Diatta *et al.* (2024) ^[74] found that the sorghum market is quite limited, with most farmers growing the crop primarily for household consumption rather than for sale, constraining commercial development.

Key areas for future research and knowledge gaps

Harish *et al.* (2024) ^[73] underscored the urgent need to intensify research on germplasm collection, protection, and evaluation. Genomic integration is imperative for the successful development of high-yielding cultivars, refinement of processing techniques, and implementation of effective policy interventions (Harish *et al.*, 2024) ^[73]. Extension efforts are crucial to combat the social stigma that limits sorghum adoption. Further research is needed on the allelopathic effects of sorghum within cropping systems, improving ratoon cultivation techniques, and developing integrated pest and nutrient management strategies specifically designed for sorghum-based systems.

Conclusion

Sorghum-based cropping systems in the tropics present a highly promising avenue for sustainable agriculture, offering resilience against climate variability, soil degradation, and water scarcity while enhancing food security and livelihoods for smallholder farmers. By integrating sorghum with legumes or other cereals in intercropping and rotation models, these systems boost yields, enhance nutritional diversity, promote biodiversity, and reduce dependency on chemical inputs, aligning with global climate-smart farming goals. With ongoing advancements in breeding for drought-tolerant varieties and precision agronomy, sorghum stands poised to drive transformative gains in tropical agroecosystems, fostering economic viability and environmental stewardship for generations to come.

Acknowledgements

The present study was supported by College of Agriculture, Vellayani, Thiruvananthapuram, Kerala Agricultural University and AICRP-IFS, Integrated Farming System Research Station, Karamana, Thiruvananthapuram by providing infrastructure and useful resources. Claude (Anthropic) was used to assist with language refinement during preparation of this review. All scientific content, data interpretation, and conclusions remain the sole responsibility of the author.

Disclaimers

The views and conclusions expressed in this article are solely those of the authors and do not necessarily represent the views of their affiliated institutions. The authors are responsible for the accuracy and completeness of the information provided, but do not accept any liability for any direct or indirect losses resulting from the use of this content.

Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this article. No funding or sponsorship influenced the design of the study, data collection, analysis, decision to publish, or preparation of the manuscript.

References

1. The World Bank Group. Population, total [data table]. Washington, D.C.: World Bank; 2026. <https://data.worldbank.org/indicator/SP.POP.TOTL>
2. Food and Agriculture Organization of the United Nations. World food and agriculture: statistical yearbook 2024. Rome: FAO; 2024.
3. Food and Agriculture Organization of the United Nations. Sustainable agricultural growth in the tropics. Rome: FAO.
4. National Geographic Society. Tropics. Washington, D.C.: National Geographic; 2026. <https://education.nationalgeographic.org/resource/tropics/>
5. United Nations Academic Impact. Enhancing understanding of the tropics. New York: United Nations; 2026. <https://www.un.org/en/academic-impact>
6. Food and Agriculture Organization of the United Nations, International Crops Research Institute for the Semi-Arid Tropics. The world sorghum and millet economies: facts, trends and outlook. Rome: FAO; 1996.
7. Crop Trust. Sorghum. Bonn: Crop Trust; 2026. <https://www.croptrust.org/news-events/campaigns/crop-conservation-strategies/sorghum/>
8. Rao BD, Bhaskarachary K, Christina MDA, Devi GS, Tonapi VA. Nutritional and health benefits of millets. Hyderabad: ICAR-Indian Institute of Millets Research; 2017.
9. Rasika A, Chavan SM, Ghatge J, Gopi S, Prathapan K. Review paper on millet: production, nutrients, processing, and food products for health and sustainability. International Journal of Environment, Agriculture and Biotechnology. 2024;9(3):88-103.
10. Kole C, Muthamilarasan M, Henry R, Edwards D, Sharma R, Abberton M, *et al.* Application of genomics-assisted breeding for generation of climate resilient crops: progress and prospects. Frontiers in Plant Science. 2015;6:563.
11. Mohanan MM, Vijayakumar A, Bang-Berthelsen CH, Mudnakudu-Nagaraju KK, Shetty R. Millets: journey from an ancient crop to sustainable and healthy food. Foods. 2025;14(10):1733.
12. Sharma N, Sahu JK, Bansal V, Esua OJ, Rana S, Bhardwaj A, *et al.* Characterization, processing and food applications of millet and pseudomillet proteins. Food Research International. 2023;164:112310.
13. Verma A, Khurana SC. Guidance notes version 2: millets. New Delhi: Food Safety and Standards Authority of India; 2020.
14. Bhat BV, Rao BD, Tonapi VA. The story of millets. Bengaluru & Hyderabad: Karnataka State Department of Agriculture and ICAR-Indian Institute of Millets Research; 2018.
15. Eeswaran R, Nejadhashemi AP, Miller SR. Evaluating the climate resilience in terms of profitability and risk for a long-term corn-soybean-wheat rotation under different treatment systems. Climate Risk Management. 2021;32:100284.
16. Wilson ML, VanBuren R. Leveraging millets for developing climate resilient agriculture. Current Opinion in Biotechnology. 2022;75:102683.
17. Debangshi U. Millets: resiliency towards climate change. Just Agriculture. 2022;3(1):1-4.
18. Ishaq T, Masood A, Palmo T, Dolker T, Khatoon A, Rashid S, *et al.* Climate resilience of millets: a sustainable solution for future agriculture. International Journal of Research in Agronomy. 2025;8(5):744-754.
19. Mishra B, Ashaq M, Gulaiya S, Dutta A, Jigile S. Climate change resilience: the role of millets in food security. In: Climate change and agricultural research. New Delhi: Books & Texts; 2024. p. 45-60.
20. Kajala K, Covshoff S, Karki S, Woodfield H, Tolley BJ, Dionora MJA, *et al.* Strategies for engineering a two-celled C4 photosynthetic pathway into rice. Journal of Experimental

- Botany. 2011;62(9):3001-3010.
21. Macrae R, Robinson RK, Sadler MJ, editors. Encyclopaedia of food science, food technology and nutrition. San Diego: Academic Press; 1993.
 22. Gopalan C, Ramasastri BV, Balasubramanian SC. Nutritive value of Indian foods. Hyderabad: National Institute of Nutrition, Indian Council of Medical Research; 1996.
 23. Hosmani MM, Chittapur BM. Sorghum production technology. Dharwad: Sarasijakshi M. H.; 1997.
 24. Taylor JRN, Schussler L. The protein compositions of the different anatomical parts of sorghum grain. *Journal of Cereal Science*. 1986;4(4):361-369.
 25. Longvah T, Ananthan R, Bhaskarachary K, Venkaiah K. Indian food composition tables 2017. Hyderabad: National Institute of Nutrition, Indian Council of Medical Research; 2017.
 26. Ciacci C, Maiuri L, Caporaso N, Bucci C, Del Giudice L, Massardo DR, *et al.* Celiac disease: *in vitro* and *in vivo* safety and palatability of wheat-free sorghum food products. *Clinical Nutrition*. 2007;26(3):344-350.
 27. Thakur DK, Pawan P, Singh A, Tripti V, Alka G. Potential health benefits of vegan dairy products using Indian millets: a review. *International Journal of Statistics and Applied Mathematics*. 2023;8(5S):910-914.
 28. Vijayreddy D, Reddy MB. Millets and its importance. *Trends in Agriculture Science*. 2023;2(1):86-90.
 29. Food and Agriculture Organization of the United Nations. Sorghum post-harvest operations. Rome: FAO; 1999.
 30. Aruna C, Visarada KBRS. Other industrial uses of sorghum. In: Aruna C, Visarada KBRS, Bhat BV, Tonapi VA, editors. *Breeding sorghum for diverse end uses*. Duxford: Woodhead Publishing; 2019. p. 271-292.
 31. Foreign Agricultural Service, United States Department of Agriculture. Production — sorghum. Washington, D.C.: USDA FAS; 2026.
<https://www.fas.usda.gov/data/production/0459200>
 32. Charyulu KD, Afari-Sefa V, Gumma MK. Trends in global sorghum production: perspectives and limitations. In: Wani SP, Gopalakrishnan S, editors. *Omics and biotechnological approaches for sorghum improvement*. Singapore: Springer; 2024. p. 1-19.
 33. Foreign Agricultural Service, United States Department of Agriculture. India sorghum area, yield and production. Washington, D.C.: USDA FAS; 2026.
<https://ipad.fas.usda.gov/countrysummary/Default.aspx?id=IN&crop=Sorghum>
 34. Reddy TY, Reddy GHS. Principles of agronomy. 6th ed. Ludhiana: Kalyani Publishers; 2023. p. 769-790.
 35. Palaniappan SP, Sivaraman K. Cropping systems in the tropics: principles and management. 2nd ed. New Delhi: New Age International Publishers; 2006.
 36. Portmann FT, Siebert S, Döll P. MIRCA2000 — global monthly irrigated and rainfed crop areas around the year 2000: a new high-resolution data set for agricultural and hydrological modeling. *Global Biogeochemical Cycles*. 2010;24(1):GB1011.
 37. Siebert S, Portmann FT, Döll P. Global patterns of cropland use intensity. *Remote Sensing*. 2010;2(7):1625-1643.
 38. Waha K, Dietrich JP, Portmann FT, Siebert S, Thornton PK, Bondeau A, *et al.* Multiple cropping systems of the world and the potential for increasing cropping intensity. *Global Environmental Change*. 2020;64:102131.
 39. Johnson DE, Humphreys E. Enhancing the productivity and sustainability of cropping systems in the coastal zones of tropical deltas of Asia. *Field Crops Research*. 2021;263:108059.
 40. Anderson WR, Seager R, Baethgen W, Cane M. Crop production variability in North and South America forced by life cycles of the El Niño Southern Oscillation. *Agricultural and Forest Meteorology*. 2017;239:151-165.
 41. Prasad R. Textbook of field crops production: foodgrain crops. Vol. 1. 11th ed. New Delhi: Indian Council of Agricultural Research; 2022. p. 137-181.
 42. International Crops Research Institute for the Semi-Arid Tropics. Sorghum in the eighties: proceedings of the international symposium on sorghum. Vol. 2. Patancheru: ICRISAT; 1981.
 43. Ji Z, Shi Y, Jiang L, Wang X, Zhu G, Zhou G. Double-cropping systems based on maize, sorghum, and alfalfa: impact of annual combination on biomass and nutritional yield. *Agronomy*. 2025;15(1):83.
 44. Kassie BT, Hengsdijk H, Rötter R, Kahiluoto H, Asseng S, Van Ittersum M. Adapting to climate variability and change: experiences from cereal-based farming in the Central Rift and Kobo Valleys, Ethiopia. *Environmental Management*. 2013;52(5):1115-1131.
 45. Clara R, Casamalthuapa NV, Cordova RH, Amaya EC, Guiragossian V. Sorghum improvement in association with maize. San Salvador: CENITA/ICRISAT.
 46. Onuwa GC. Mitigating risks in smallholder sorghum production systems. *Agribusiness Management in Developing Nations*. 2023;1(2):41-44.
 47. Magnolo F, Dekker H, Decorte M, Bezzi G, Rossi L, Meers E, *et al.* The role of sequential cropping and Biogasdoneright in enhancing the sustainability of agricultural systems in Europe. *Agronomy*. 2021;11(11):2102.
 48. Radulovich R. Sequential cropping as a function of water in a seasonal tropical region. *Agronomy Journal*. 2000;92(5):860-867.
 49. Reda F, Verkleij JAC, Ernst WHO. Relay cropping of sorghum and legume shrubs for crop yield improvement and *Striga* control in northern Ethiopia. *Journal of Agronomy and Crop Science*. 2005;191(1):20-26.
 50. Zhou Y, Huang J, Li Z, Wu Y, Zhang J, Zhang Y. Yield and quality in main and ratoon crops of grain sorghum under different nitrogen rates and planting densities. *Frontiers in Plant Science*. 2022;12:778663.
 51. Meena RS, Sihag SK. *Agronomy facts for competitions*. 6th ed. New Delhi: Jain Brothers; 2024. p. 570-578.
 52. Shimelis H, Assefa A, Tongoona P, Mengistu F, Laing M, Ayele D. Sorghum production systems and constraints under drought-prone agro-ecologies of Ethiopia. *South African Journal of Plant and Soil*. 2016;33(3):207-217.
 53. Bean B. Sorghum powerful tool in a rotation. *Dodge City: High Plains Journal*; 2023.
<https://www.highplainsjournal.com/sorghum-powerful-tool-in-a-rotation>
 54. Hussain MI, Danish S, Sánchez-Moreiras AM, Vicente O, Jabran K, Chaudhry UK, *et al.* Unraveling sorghum allelopathy in agriculture: concepts and implications. *Plants*. 2021;10(9):1795.
 55. Ullah R, Aslam Z, Attia H, Sultan K, Alamer KH, Mansha MZ, *et al.* Sorghum allelopathy: alternative weed management strategy and its impact on mung bean productivity. *Life*. 2022;12(9):1359.
 56. Glaze-Corcoran S, Hashemi M, Sadeghpour A, Jahanzad E, Afshar RK, Liu X, *et al.* Understanding intercropping to improve agricultural resiliency and environmental

- sustainability. *Advances in Agronomy*. 2020;162:199-256.
57. Francis CA. Future perspectives of multiple cropping. In: Francis CA, editor. *Multiple cropping systems*. New York: Macmillan Publishing Company; 1986. p. 351-370.
 58. Singh O, Arya HPS. Productivity potential of maize and soybean intercropping system in western Uttar Pradesh. *International Journal of Current Microbiology and Applied Sciences*. 2020;9(Special Issue 11):3740-3743.
 59. ICAR-Indian Institute of Millets Research. Sorghum intercropping with pigeonpea. Hyderabad: ICAR-IIMR. https://www.millets.res.in/sorg_technologies.php
 60. Sujathamma P, Nedunchezhiyan M. Evaluation of sorghum based intercropping systems for rainfed Vertisols. *Indian Journal of Agricultural Research*. 2024;58(2):290-294.
 61. Food and Agriculture Organization of the United Nations. Guidelines: land evaluation for irrigated agriculture. FAO Soils Bulletin 55. Rome: FAO; 1985.
 62. Chaudhary R, Gupta S, Gupta K, Singh M, Kohli A. Effect of intercropping on growth, yield and profitability of sorghum, pearl millet and cowpea. *Journal of Pharmacognosy and Phytochemistry*. 2020;9(5):1026-1030.
 63. Nagla N, El Naim AM, Ibrahim KA. Assessment of groundnut and sorghum intercropping. *Innovation in Science and Technology*. 2022;1(3):1-7.
 64. Verma SS, Joshi YP, Saxena SC. Effect of row ratio of fodder sorghum in pigeonpea intercropping system on productivity and economics under rainfed conditions. *Indian Journal of Agronomy*. 2005;50(2):123-125.
 65. Hiebsch CK, McCollum RE. Area-x-time equivalency ratio: a method for evaluating the productivity of intercrops. *Agronomy Journal*. 1987;79(1):15-22.
 66. Darshini DS, Ramanathan S, Reddy DV, Prabu P, Karthikeyan P. Economic advantage of sorghum based intercropping system for western zone of Tamil Nadu, India. *Asian Research Journal of Agriculture*. 2024;17(3):152-158.
 67. Ram SN, Singh B. Physiological growth parameters, forage yield and nitrogen uptake of sorghum as influenced with legume intercropping, harvesting time and nitrogen level. *Indian Journal of Agronomy*. 2002;48(1):38-41.
 68. Reddy KJ, Madhu Bindu SA, Hussain M, Uma Devi M, Maheshwaramma S. Nutritional composition of yellow pericarp sorghum: a review. *International Journal of Environment and Climate Change*. 2022;12(12):1732-1738.
 69. Tanwar R, Panghal A, Chaudhary G, Kumari A, Chhikara N. Nutritional, phytochemical and functional potential of sorghum: a review. *Food Chemistry Advances*. 2023;3:100501.
 70. Duvvada SK, Maitra S. Sorghum-based intercropping system for agricultural sustainability. *International Journal of Natural Sciences*. 2020;10(60):20306-20313.
 71. Hadebe ST, Modi AT, Mabhaudhi T. Drought tolerance and water use of cereal crops: a focus on sorghum as a food security crop in Sub-Saharan Africa. *Journal of Agronomy and Crop Science*. 2017;203(3):177-191.
 72. Dunjana N, Dube E, Chauke P, Motsepe M, Madikiza S, Kgakatsi I, *et al.* Sorghum as a household food and livelihood security crop under climate change in South Africa: a review. *South African Journal of Science*. 2022;118(9/10):35-40.
 73. Harish MS, Bhuker A, Chauhan BS. Millet production, challenges, and opportunities in the Asia-Pacific region: a comprehensive review. *Frontiers in Sustainable Food Systems*. 2024;8:1386469.
 74. Diatta C, Tovignan TK, Sine B, Ifie BE, Faye JM, Diatta-Holgate E, *et al.* Farmers' production constraints, preferred varietal traits and perceptions on sorghum grain mold in Senegal. *Heliyon*. 2024;10(9):e30221.