www.nature.com/scientificreports

scientific reports

Check for updates

OPEN

Enhancing food and nutrition security in Himalayan foothills with neglected and underutilized millets

Raja Rajendra Timilsina[1]✉, Hari Prashad Joshi[2] & Dil Bahadur Rahut[1]

Global food production predominantly depends on a limited number of cereal crops; however, numerous other crops have the potential to support the nutrition and economy of many local communities in developing countries. The different crop species characterized as having relatively low perceived economic importance or agricultural significance are known as underutilized crops. Millet is one of the underutilized crops with significant potential to address nutrient and hunger-related challenges in many developing countries like Nepal due to its versatility and climate resilience. Little is known about the determinants of adoption, cultural importance, and nutritional benefits of millet. Therefore, this study uses data from 1988 to 2019 and examines trends in millet production and its climate resilience, employing the Dynamic Ordinary Least Square Method. Results indicate that fertilizer use, cultivated area, and rural population significantly impact millet production in Nepal, while mean temperature has a negative but insignificant effect. The findings suggest that climate change does not significantly impact millet production. Millet is well adapted to challenging environments and offers superior nutritional value, suggesting that integration of millet into modern agriculture could be a valuable tool for creating a more sustainable, equitable, resilient, and healthy agrifood system that benefits both people and the planet. This research provides valuable insights for policymakers to enhance underutilized crops such as millet and implement strategies to integrate them into central agrifood systems. It also has a more considerable socio-economic impact on local communities.

Keywords Food security, Nutrition security, Himalayan foothills, Millet potential, Climate-resilient crops, Sustainable agriculture

Global food security faces major challenges, with 820 million people worldwide enduring chronic hunger that requires increased agricultural productivity and diversification of nutrient-dense crops[1]. Nearly half of the world's calorie and protein intake depends on three staple crops: maize, wheat, and rice. Although around 12,650 plant species are edible, but people rely on only around 30 to meet 95% of global food needs, leaving most edible plants outside the main diet[2]. There are crop species characterized as having relatively low perceived economic importance or agricultural significance and receiving relatively little research, limited geographic distribution, low adoption, and no support from policymakers, technology providers, donors, and breeders that are termed as neglected and underutilized crop species (NUCS) or minor or orphan crops[3–5]. Once central to local diets and livelihoods, underutilized crops now receive little attention from agricultural research, plant breeders, and policymakers[6,7]. On the other hand, rice, maize, and wheat demand fertile land, irrigation, and intensive management, and receive higher priority from governments and researchers but are still remainhighly vulnerable to climate[8]. Stable crops, such as rice, wheat, and maize, provide primary caloric supplies with restrictive dietary diversity.

Underutilized crops grow well in marginal conditions with minimal inputs, adapt to diverse habitats, offer straightforward cultivation, store well, and carry unique nutritional benefits[9]. Underutilized crops are of essential value for food security and economic resilience in low and middle-income countries, especially mountainous and tropical regions rich in agrobiodiversity[10]. Millet, for example, grows mainly in Asia and Africa and shows the potential to strengthen nutrition, food security, and sustainable agriculture[9]. Nutritionally rich, drought-tolerant, and adaptable to challenging soils, millets are promising, but underutilized crops with the potential to improve food security and nutritional diversity[11]. In traditional diets, millets have historical importance, but modern agriculture has largely replaced them with a limited selection of staple crops[12]. Reintroducing these

[1]Asian Development Bank Institute, Research, Tokyo 100-6008, Japan. [2]Nepal College of Management, Kathmandu University, Kathmandu, Nepal. ✉email: rtimilsina@adbi.org

underutilized crops into our food systems can boost food security, improve nutrition, support income generation, and promote ecological sustainability[13]. However, challenges in supply chains, low consumer awareness, and the stigma of labelling these crops as "famine food" or "food for the poor" hinder their expansion[14]. Modern agricultural practices also have amplified these issues by reducing their diversity and removing them from the production system[15,16].

Case of Nepal

Since the beginning of the 18th century or earlier, the indigenous communities of Nepal, such as the Newars, Majhis, Magars, and others, have had a long history of growing millet as a staple crop[17]. During the 18th century, there was a Malla dynasty in Kathmandu, where Khas people migrated from Kashmir through the Kumau and Garhwal regions of India, ultimately settling in Nepal's hilly areas[18]. Historically, the Khas were agriculturalists known for their millet cultivation expertise and also introduced crops such as barley, wheat, and sesame[19,20]. In the Kathmandu Valley, fertile lands were dominated by Newar farmers who grew paddy, while unirrigated areas were farmed by Tamang and Magar communities cultivating millet and maize. The Khas settled in these (unirrigated) lands and continued millet farming. Over time, interactions between the Khas and local communities, such as those under Malla rule, led to agricultural practices and language exchanges. The Khas were eventually permitted to cultivate irrigated lands, further integrating their agricultural knowledge into the region[18]. The Khas contributed significantly to developing what is now the Nepali language (Khas Bhasa) and introduced their traditional farming techniques to the local communities. Over time, Khas people were integrated into Nepalese society and were categorized within the Hindu caste system, with many identifying as Chhetri and Brahmins (Bahun)[20]. Millets were a staple crop for upland areas with scarce water resources and were essential for food security and nutrition in the region. During the early 19th century, rural people cultivated wheat and rice to pay taxes while subsisting on barley, maize, millet, and supplemented by fruits and herbs[19]. Also, they used millet, such as kodo, sama, and kaguno, exclusively to pay tax to the local government, highlighting the significance of millet as a subsistence crop focused on revenue generation[20]. The semi-nomadic Khamba tribes, who lived in Karnali, Seti, Rapti, and Bheri during the mid-20th century, also relied heavily on millet cultivation. They cultivated millet, buckwheat, kaguno, and marse, which sustained their semi-nomadic lifestyles and livelihoods[20]. Mongolian groups in the Himalayan region have relied on wild plants and hunting since prehistoric times[18]. Over time, they transitioned to farming, cultivating crops like millet, maize, and mustard, particularly in the hilly terrains where rice cultivation was challenging. This adaptation laid the foundation for millet as a staple crop in the Himalayan agricultural landscape. Similarly, during the early 20th century, indigenous communities such as the Majhis and the Thamis were deeply intertwined with millet cultivation and its cultural significance[18]. The Majhis, who lived along the Sunkoshi and Tamakoshi riverbanks, relied on millet alongside maize and paddy as a key crop[20]. Millet featured prominently in their rituals and festivals, including the Aitabare festival, where millet flour was used to make baabar bread, symbolizing blessings and prosperity[21]. Millet liquor "rakshi" also played a central role in their festive and spiritual practices. Thami community, predominantly settled in eastern Nepal's Dolakha district, cultivated millet extensively on rainfed lands. Traditional millet varieties like "dallo mudke kodo," "chyalthye kodo," "juwain kodo," and "sunkoshi kodo" were vital to their agricultural repertoire[22]. Post-harvest, millet was processed using tools like the "gyalbi" for de-husking, and grain was considered an essential food source, especially during rice scarcity. Nutritious and energizing millet-based foods such as dhedo and roti sustained the Thamis throughout the year[22].

Figure 1 illustrates the traditional Nepali unit of volume, Paathi, commonly used to measure grains. One Paathi is approximately 4.5 kilograms, providing a standard for analyzing historical grain prices in Jumla during 1779[21]. Rice was priced at 8 rupees per Paathi, making it relatively affordable compared to other grains. This accessibility suggests its widespread cultivation and availability in the region. Conversely, millet (kodo) was priced at 12 rupees per Paathi, indicating a higher cost. The elevated price of millet might reflect its nutritional value, cultural importance, or limited availability compared to rice. Barley, at 16 rupees per Paathi, was the most expensive grain listed. The higher cost of barley may have stemmed from its dual use as a staple food, its potential demand for brewing purposes, and its possible scarcity in the region. These price variations highlight the economic and cultural factors influencing grain valuation in 18th-century Jumla, emphasizing the relation between agricultural production, dietary preferences, and market dynamics[20]. Millets have played a significant socio-economic role in Nepalese agrarian society, extending beyond their function as a food crop to serving as an economic instrument in historical contexts. Millet was often used as a form of payment for taxes and wages, particularly in rural areas where monetary systems were less established. Its value in barter transactions highlights its importance in sustaining local economies. Historical records suggest that millet's resilience to adverse growing conditions made it indispensable during crop failure, providing a community safety net.

Nepal is recognized for its rich biodiversity that is a testament to its wide range of plant species. The country possesses 577 cultivated species as major crops, while 484 species are indigenous and are found in a different region[23,24]. The rich biodiversity of Nepal comes from it's varied agroecological zones, ranging from the lowland Tarai to the high Himalayan regions, each supporting and suitable for different types of crops. Nepal is also one major country that is home to several neglected and underutilized crops (NUCs), such as proso millet (chino), foxtail millet (kaguno), sorghum (junelo), red amaranth (laal saag), wild millet (baale banso), wild rice (jungali dhaan), wild asparagus (ban kurilo), taro (pidalu, karkalo), yam (ban tarul), drumstick (sital chini), tartary buckwheat (titephapar), custard apple (sita fal), pokeberry (jaringo), wild fern (niuro), singing nettle (sisnu), ivy gourd (kundruk), etc[24,25]. These NUCs are known for their high adaptability to changing climates, ability to grow in marginal soils, and nutritional richness, making them valuable for food and nutrition security in Nepal. NUCs currently contribute a small portion to the overall food basket in Nepal, and they are cultivated on a relatively small scale compared to major crops such as rice, wheat, and maize. The productivity of these crops varies, such that foxtail millet yields 0.99 tons per hectare, proso millet 0.819 tons per hectare, and red

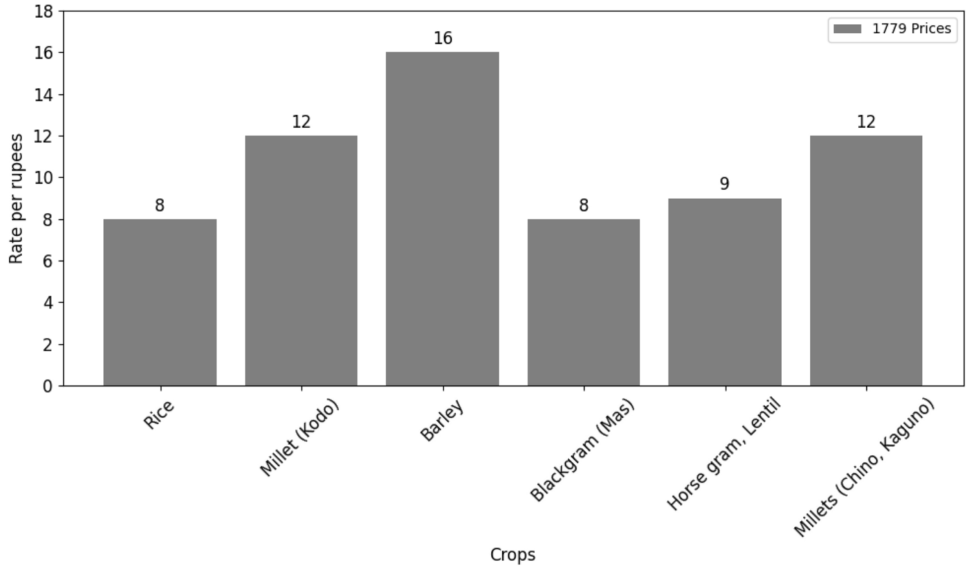

Fig. 1. The price of food grain in Jumla in 1779 at a unit "Paathi" current market price for rice, kodo, and chino, kaguno is Rs. 1665, 585 and 1800, respectively. The dollar conversion is \$ 1 = Rs 136[21].

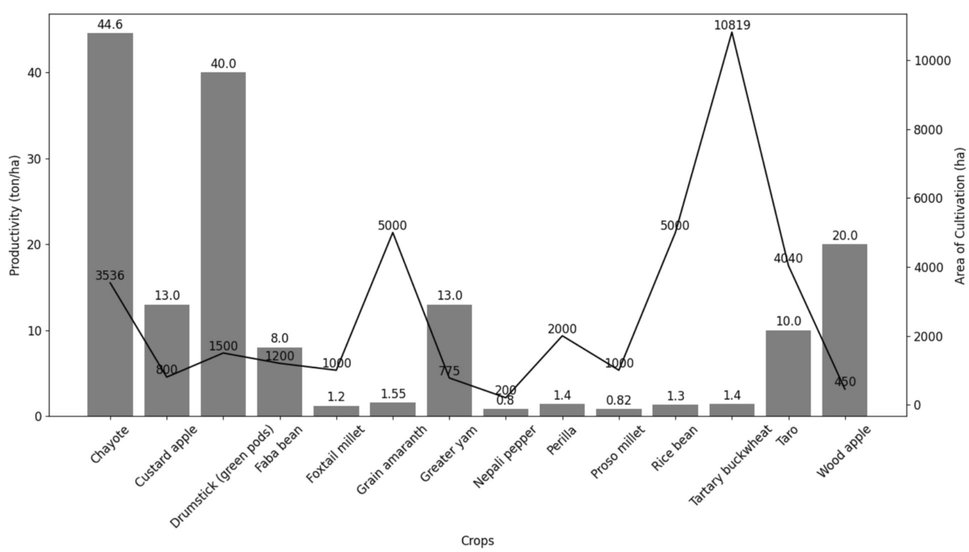

Fig. 2. Productivity and area under cultivation for NUCS Crops y-axis right (Source: Ministry Of Agriculture and Livestock Development, 2017/18, 2021/22).

amaranth 1.55 tons per hectare. In contrast, other NUCs, such as taro and yam, have higher productivity, at 10 and 13 tons per hectare, respectively[24,26,27]. Figure 2 shows information on productivity given by the right side of the y-axis and the cultivation area of various NUCs demonstrated by the line graph on the left side of the y-axis. The productivity is mostly higher than 1 for most of NUCs. These crops receive minimal attention in improving their yield, resilience, and adaptability to changing environmental conditions. Many underutilized crops produce smaller harvests and have poor shelf lives, reducing their appeal to large-scale production and trade. The underutilized crops are labor-intensive and market challenges also hinder the adoption of these crops. The rise of competitive crops, such as rice, wheat, and maize, which dominate agricultural markets and receive substantial research and policy support, squeezes these crops out of market niches, further neglecting these underutilized crops. NUCs suffer social, economic, environmental, agronomic and political challenges.

Neglected and underutilized crops (NUCs) are crucial in promoting sustainability, ecological diversification, economic empowerment of rural communities, and enhancing nutritional and health security[28]. Recently, there has been a growing global interest in rediscovering traditional nutrient-rich food sources[29]. Among these, millet stands out as a promising solution, offering both nutritional and agricultural benefits, particularly in addressing the challenges of food production under the pressures of climate change. Also, for Nepal, millet is an important

Crop name	Protein (g)	Fat (g)	Carbohydrate (g)	Energy (kcal)	Ca (mg)	Crude fibre (g)	Fe (mg)
Cereals							
Rice	6.8	0.5	78.2	362	7.49	7.49	0.65
Wheat	11.8	1.5	71.2	348	39.36	10.59	3.97
Maize	8.90	3.28	73.94	365	21.40	2.7	0.7
Millets							
Sorghum	10.8	3.1	70.7	329	586	6.3	20
Pearl Millet	11.8	4.8	67	363	42	1	8
Finger Millet	7.3	1.3	72	336	392	7.16	4.72
Foxtail Millet	12.3	4.3	60.9	351	31	8	2.8
Proso Millet	12.5	3.1	70.4	364	14	3.91	0.8
Little Millet	7.7	4.7	67	329	16.06	1.93	1.26
Barnyard Millet	6.2	2.2	65.5	300	20	1.75	5
Kodo Millet	8.3	1.4	65.9	353	39.63	6.12	3.55

Table 1. Comparing the number of nutrients found in 100 gm of cereals and millets.

Regions	Area (ha)	Production (tons)	Yield (tons/ha)
Eastern Mountains	12,335	15,596	1.264
Eastern Hills	56,513	75,892	1.343
Eastern Terai	3,688	4,364	1.183
Central Mountains	21,040	26,793	1.273
Central Hills	36,221	39,095	1.079
Central Terai	2,570	2,433	0.967
Western Mountains	92,932	1,03,598	1.115
Western Hills	–	–	–
Western Terai	495	489	0.988
Mid-west Mountains	10,833	9,971	0.92
Mid-west Hills	11,336	12,955	1.143
Mid-west Terai	15	15	1
Far-west Mountains	6,800	5,735	0.843
Far-west Hills	8,468	9,418	1.112
Far-west Terai	350	350	1
Total Mountains and Hills	205,470	240,958	1.1584
Total Terai	7,118	7,651	1.0236

Table 2. Region wise Millet production in Nepal, Source:- MOALD, 2016/17. Sea level to 600 meters:-Terai, 600m to 2000m:- Hills, 2000m:- 3500m- Mountains

crop after rice, wheat, and maize in terms of production area and food security. The millet cultivation spans a remarkable altitude range of approximately 60m to 3600m above sea level and contributes 1. 19% to the Gross Domestic Product of Agriculture (AGDP)[17,30,31]. In Nepal, approximately 39. 7% (58,512.71 km^2) of land area is suitable and has a high potential for millet[31–33]. Nepal's agroecological zones also support the diversity of millets and exhibit a wide distribution across Nepal, growing in all 77 districts of the country[30,34]. The country has 12 domesticated millet species, such as (bristly foxtail millet, browntop millet, finger millet, foxtail millet, Japanese barnyard millet, job's tear millet, kodo millet, little millet, Nepalese barnyard millet, pearl millet, proso millet, sorghum), they are all resistant to cold and drought conditions[26,27,32].

Table 1 compares the nutritional content of various millet types with rice and wheat. It demonstrates that millet varieties such as pearl millet, foxtail millet, and proso millet exhibit higher protein and fat content than rice and wheat. For example, foxtail millet contains 12.3g of protein and 4.3g of fat per 100g, while rice has 6.8g of protein and 0.5g of fat. This comparison highlights the superior nutritional profile of millets, establishing them as valuable sources of essential nutrients. Similarly, Table 2 provides a comprehensive overview of millet production across different regions of Nepal based on data from the Ministry of Agriculture and Livestock Development (MOALD) for 2016/17[31]. Millets demonstrate a wide array of health benefits and possess a rich nutritional profile, making them a valuable addition to dietary practices across the globe[35]. These grains are abundant in essential nutrients, including carbohydrates, proteins, dietary fiber, vitamins, and minerals[34]. Millets are exceptionally high in magnesium, phosphorus, manganese, and iron, nutrients that play critical roles in various physiological functions, including energy production, bone health, and oxygen transport. Moreover, millets represent a significant source of essential amino acids, making them especially advantageous for individuals adhering to vegetarian or vegan diets. These amino acids are instrumental for muscle repair, growth, and overall physiological well-being. Millets' low glycemic index (GI) facilitates a gradual release of glucose into the bloodstream, providing a sustained energy supply. This characteristic renders millet a favorable option for individuals managing diabetes or those aiming to effectively regulate their blood sugar levels[36]. Rich in dietary fiber, millets promote digestive health by preventing constipation and regulating blood cholesterol levels. This fiber content contributes to enhanced satiety, aiding in weight management and control[37]. Being naturally gluten-free, millets are excellent alternatives to gluten-containing grains such as wheat, barley, and rye, making them suitable for individuals diagnosed with celiac disease or gluten sensitivity. Certain varieties of millet, particularly finger millet (ragi), are rich in antioxidants, including polyphenols and flavonoids[38]. These antioxidants are beneficial in mitigating oxidative stress and reducing cellular damage caused by free radicals. These antioxidants may also play a role in decreasing the risk of chronic diseases and associated inflammatory processes. Combining high fiber content and heart-healthy fats in millet supports cardiovascular health by lowering cholesterol levels, reducing blood pressure, and minimizing the risk of heart disease and stroke. Owing to their low caloric density, high fiber content, and ability to promote feelings of fullness, millets are advantageous for weight loss and management. Incorporating millets into dietary regimens can facilitate prolonged satiety, assisting individuals in achieving their health objectives[37]. Overall, millets emerge as a nutritious and versatile food choice that can enhance overall health and well-being. Integrating various millet types into daily meals can promote diverse nutrient intake and support a balanced, health-conscious dietary pattern.

A notable feature of finger millet, proso millet, and foxtail millet is their classification as C4 crops: plants that use a specialized C4 photosynthetic pathway[39]. This pathway allows C4 crops to capture carbon dioxide efficiently by forming a four-carbon molecule during the initial carbon fixation stage. This trait enhances productivity in hot and dry environments with intense sunlight[26,39]. This adaptation helps them conserve water and use nitrogen effectively, allowing them to thrive in low-fertility soils and under drought conditions where other crops could fail. Their resilience makes these C4 crops especially suited to the Himalayan foothills, offering a sustainable, climate-resilient option for agriculture in marginal areas[17]. In Nepalese districts like Humla, Mugu, Mustang, and Manang, these "Himalayan superfoods" rank as primary or secondary staples, serving as essential local food and nutrition security sources amid high poverty levels[31]. This positions millet as vital contributors to sustainable food systems and climate adaptation strategies in regions vulnerable to climate change[17,30],

Millets are deeply embedded in Nepal's cultural and culinary traditions, serving as a vital link between food and cultural diversity and identity[21]. Festivals and rituals across ethnic communities prominently feature millet-based foods and beverages. It is a key ingredient in traditional beverages like jand, rakshi, and tumba, which hold cultural and ceremonial significance[21]. The southern plains of Nepal, known as the Tarai, are well-suited for cultivating rice and transporting it to the hills and mountains, facilitating a vital exchange of agricultural products across ecological zones[17]. The tradition of the Tharu community to consume finger millet bread highlights the potential of fostering the interchange of crops and culinary practices between different regions and ecological niches[30]. Women play a pivotal role in preserving and diversifying millet-based culinary traditions. These include nutritious staples such as dhedo (a thick porridge), roti (flatbread), and festival-specific items like millet-based sweets and snacks. In addition, women contribute to food innovation by incorporating millet into modern products like noodles, papad, and bakery goods, ensuring its relevance in contemporary diets[40]. However, millet consumption in Nepal has declined as preferences shift towards rice, wheat, and maize, especially among younger generations who are less familiar with millet. This shift is due to urban migration and changing dietary habits. Despite their resilience and nutritional benefits, millets are often neglected in Nepalese agriculture due to low productivity, limited product diversification, and lack of awareness among producers and consumers. Millets can also offer economic opportunities by selling processed products, including "rakshi," a traditional alcoholic beverage with crucial cultural value. Ecologically, millet supports environmental sustainability by promoting beneficial insects and improving soil health. These crops are integral to the country's heritage, ecology, and environment, embodying a connection to tradition and livelihoods across Nepal.

Millet has untapped potential to increase food security, nutrition, health, and income, especially in the challenging agricultural environments of Nepal but formal research, education, and development programs largely overlook this crop[23,27,34,41]. Soil fertility is low in hilly and mountainous areas, and limited rainfall restricts farming options; however, millet can thrive in these conditions. As Nepal's fourth most important crop after rice, maize, and wheat, millet is critical in mountainous areas with limited arable land and frequent food shortages[41]. Food and Agriculture Organization (FAO), UNICEF and the World Bank have created a database to calculate the Global Hunger Index (GHI), which measures hunger severity by combining data on undernutrition, child waste, child stunting and child mortality. The indicator is weighted and combined into a single score on a 100-point scale, where low hunger is 0-9.9, moderate hunger is 10-19.9, serious hunger is 20-39.9, alarming hunger is 35-49.9, and extremely alarming hunger is 50 or more, where Nepal score 19.1, placing it in the "moderate" hunger category[42]. With this moderately high level of hunger, Nepal urgently needs to diversify and strengthen its local food systems to improve food access and resilience. Population growth and increasing food demand add further pressure, with projected edible cereal requirements expected to reach 8.854 million metric tons by 2030, 10.07 million metric tons by 2040, and 11.46 million metric tons by 2050. The achievement of these targets will depend on the maintenance of productivity levels of 3.10 tons per hectare and an annual agricultural growth rate of 2.26%, with a population growth rate of 1.3% per year estimate[26]. Given these demands, millet's ability to thrive in the Himalayan hilly and mountainous regions could be vital to ensuring Nepal's food and nutritional security. Nepal can address the critical food demand and strengthen regional and national food security in the years ahead, focusing on the potential of millet.

Past studies highlight the critical role of fertilizers in millet cultivation, influenced by agricultural practices, socio-economic conditions, and the necessity of nitrogen fertilizers[43]. Hayashi et al.[44] demonstrated that micro-dosing with fertilizer increases millet yields regardless of application timing. Eyshi Rezaei et al.[45] found that using crop wastes and mineral fertilizer enhances pearl millet production more effectively than using either of the inputs alone. Sharma[46] emphasized that combining fertilizers with farmyard manure positively impacts harvesting sequences and soil quality for millet production. Several studies have examined millet's response to climate change, such that Bewket[47] confirmed rainfall variability significantly affects cereal production, including millet, in Ethiopia. Maharjan[48] noted that intense, concentrated rainfall severely impacts crop productivity, but off-season experiments showed that cowpea and pearl millet thrive under intense heat. Nelson et al.[49] identified pearl millet as particularly climate-resilient and suitable for semi-arid regions due to its high tolerance for heat and scarce water conditions. Luitel et al.[32] observed that rising temperatures, growing degree days (GDD), and decreased rainfall positively impacted finger millet production in central Nepal. Conversely, Karim et al.[50] found that millet and sorghum remained resilient to climate changes in Ghana. However, Hossain et al.[10] cautioned that early rainfalls and high temperatures during crop maturity could reduce millet yields.

Socioeconomic factors significantly influence millet production. Gitu et al.[51] found that characteristics of household heads, cultivation area, cultural factors, technological qualities of millet varieties, and agricultural knowledge positively affected finger millet production in Kenya[51]. Handschuch and Wollni[52] analyzed data from 270 households, discovering that modern seeds and fertilizers are more common in maize production than finger millet. They also found that social networks and access to extension services play a crucial role in adopting improved finger millet practices, while these factors are less significant for maize cultivation. Mukhtar et al.[53] showed that socioeconomic factors such as cooperative participation, debt, education, extension contact, family size, and off-farm incomes positively affected pearl millet production in Nigeria[53]. Population growth, increasing food prices, and urbanization present major threats to millet cultivation, especially for low-income individuals in the Asia-Pacific region[12]. Millet production remains popular in rural areas due to its low water requirements. However, rapid urbanization alters food accessibility and sustenance means, shifting economies from agriculture-based to alternative income sources[54,55]. However, Bhatt et al. (2023) highlighted the increasing urban demand for millet flour, noting its potential health benefits for diabetes, cardiovascular issues, obesity, skin conditions, cancer, and celiac disease[56]. Ma et al.[57] and Lubadde et al.[58] emphasized the role of cultivated areas in increasing millet production. However, Gebreyohannes et al.[59] found a negative relationship between cultivated area and millet production. Saxena et al.[11] reviewed studies showing a decline in millet production areas due to governmental support for key grains like rice and wheat. They highlighted the environmental benefits of cultivating millet over major cereals, suggesting a shift to mitigate food insecurity and environmental stress in regions most impacted by climate change. Millet cultivation has declined due to government support for other grains, but millet's environmental benefits can help address food insecurity and climate challenges.

Despite extensive research on factors affecting millet production, there is a gap in studies focusing on millet's climate resilience. Most research emphasizes production determinants without thoroughly investigating millet's role in ensuring food security amid climate change. This study aims to fill this gap by examining millet's climate resilience using Nepal as a case study from 1980 onwards. It will provide insights into how underutilized crops like millet can enhance food security and adapt to climate challenges, offering valuable data for policymakers and agricultural stakeholders. This study analyzes millet production dynamics in Nepal, emphasizing the broader benefits of millet beyond production determinants. It contributes to the literature in two ways: first, by being the first study on millet production in Nepal using time series data; second, by providing insights into how Nepal's climate influences millet production. It also includes a trend analysis of millet compared with major crops like rice, wheat, maize, and barley.

Results

Table 3 outlines the determinants of millet production across various Asian regions. In India, the positive factors for better millet production are land ownership, irrigation, agricultural income, and cultivated land, while negative factors are education, livestock, and distance from major markets[60]. In Nepal, subsidies, local tourism, increased agro-based industries, and farmer motivation are the factors that positively impact millet production. In contrast, high-yielding varieties, marketing issues, and a preference for other cereals are negative determinants[61]. In China, cultivated areas, average temperatures, and precipitation positively affect millet production, while longitude and latitude are negative factors for millet production[57]. Table 4 highlights the determinants of millet production in African regions. In North Africa, specifically Ethiopia, positive determinants include chemical fertilizers and other agricultural inputs, but the rainfall variability trend is a negative factor[47,59]. In East Africa, Tanzania's positive factors are the education level of household heads, market price, and household food priority, while in Uganda, positive determinants include cultivated area, spouse age, and producers' experience. However, the age of household heads, the amount of seed planted, and market distance negatively affect millet production[58,62]. In West Africa (Nigeria), positive factors include credit facility, education level, cooperative membership, extension contact, household size, off-farm income, and improved see[50]. Other African regions exhibit similar trends with

Author	Region/Country	Positive determinants for millet production	Negative determinants for millet production
Society of Plant Genetic Resources[60]	South Asia/India	Land owned, Irrigation, Agricultural income, Cultivated land	Education, Livestock, Distance from major market
Gyawali[61]	South Asia/Nepal	Subsidy, Improving tourism, Increase in agro-based industries, Farmers' motivation	High yielding varieties, Marketing, Preference towards cereal
Ma et al[57]	South Asia/China	Cultivated area, Average temperature, Precipitation	Longitude, Latitude

Table 3. Determinants for Millet production in Asian regions and countries.

Author	Region/Country	Positive determinants for millet production	Negative determinants for millet production
Bewket[47]	North Africa/Ethiopia	Chemical fertilizer, Other agricultural inputs	Rainfall amount, Rainfall variability, Rainfall trend
Abdallah[62]	East Africa/Tanzania	Education level of household head, Pearl millet price, Household food priority	
Lubadde et al.[58]	East Africa/Uganda	Cultivated area, Spouse age, Producers' experience	Age of household head, Amount of seed planted, Market distance
Mukhtar et al.[53]	West Africa/Nigeria	Credit, Education level, Cooperative membership, Extension contact, Household size, Off-farm income, Improved seed	Producer age, Household size
Oladimeji et al.[74]	West Africa/Nigeria	Inorganic fertilizer, Organic manure, Agrochemicals	Farm size, Labor, Seed
Gebreyohannes et al.[59]	North Africa/Ethiopia	High quality grain, Marketability, Early maturity	Land size, Soil fertility, Access to fertilizer
Karim et al.[50]	West Africa/Ghana		CO2 emission, Temperature, Rainfall

Table 4. Determinants for Millet production in African regions and countries. Values are approximate based on 100 grams of each crop. Nutrient values may vary based on variety, cultivation method, and processing. Source[75,76]

varied specific factors influencing millet production. Despite regional differences, it is clear that government policies and educational awareness are crucial for improving millet production across Africa and Asia. Effective government policies can provide necessary support through subsidies, infrastructure development, and access to markets, while educational programs can enhance farmers' knowledge about modern agricultural practices, efficient resource use, and the benefits of millet cultivation. These combined efforts can significantly boost millet production, ensuring better food security and economic stability in these regions.

Table 2highlights an exciting trend in millet production across different regions of Nepal, particularly when comparing production in the mountains and hills with that in the Terai region. Each region in the table is accompanied by the area of land under millet cultivation (in hectares), the total production of millet (in tons), and the yield of millet per hectare (in tons/ha). For instance, the Eastern Mountains region, with 12,335 hectares under cultivation, yielded 15,596 tons of millet at a rate of 1.264 tons/ha. Similarly, Table 2 also shows area of cultivation, production and yield for regions like Central Mountains, Western Hills, Mid-west Terai, and Far-west Mountains. Table 2 not only presents the variations in millet production across different regions of Nepal but also highlights the influence of geographical factors such as altitude and terrain. Higher production is observed in higher altitude regions such as the Western Mountains, with 92,932 hectares yielding 103,598 tons and an average yield of 1.115 tons/ha. Conversely, the Terai regions show lower production and yield, highlighting the adaptability of millet to mountainous terrains. A note in the table specifying the altitude ranges corresponding to the Terai, Hills, and Mountains regions further enhances this understanding.

Conventionally, the Terai region has been hailed as Nepal's 'food basket' due to its fertile plains and favorable agro-climatic conditions, which foster high agricultural productivity. However, the Table 2 reveals a surprising twist, millet production is actually higher in the mountain and hill regions than in the Terai, a finding that demands our attention. For instance, while total millet production in the mountains and hills combined is higher than in the Terai, the yield per hectare is also notably greater in these regions. This indicates that despite the challenges posed by rugged terrain and higher altitudes, millet cultivation in the mountains and hills is yielding better productivity results. Several factors could contribute to this disparity. The Terai's focus on commercial agriculture, particularly cash crops like rice, wheat, and sugarcane, may lead to a lower emphasis on traditional crops like millet. Additionally, the Terai's fertile lands may be more suitable for high-yield varieties of staple crops rather than traditional grains like millet. Conversely, mountain and hill regions may have a stronger cultural and historical connection to millet cultivation, leading to greater investment and expertise in its production. The harsher environmental conditions in these regions may necessitate the cultivation of hardy and resilient crops like millet, resulting in a more focused effort towards its cultivation and higher yields per hectare. Overall, Table 2 serves as a valuable resource for understanding the distribution of millet production in Nepal, aiding policymakers, researchers, and agricultural stakeholders in strategic planning and decision-making processes related to millet cultivation and food security initiatives.

Figures 3, 4, 5, 6 and 7 shows the trends in rice, maize, wheat, barley and millet production and productivity over the years 1981 to 2020. Both production and productivity have seen a consistent upward trend beginning at around 2.0 productivity and have gone up to 4.0. It has doubled over the period of 40 years, and this increase can be attributed to improved farming techniques, better irrigation methods, and possibly favorable climatic conditions. The graph indicates that enhancements in agricultural practices have positively impacted rice yields, making it a reliable staple food. Figure 4 shows trends in maize and reveals a consistent increase in both production and productivity from less than 1.0 in 1981 to close to 3.0 in 2020, suggesting significant improvements in agricultural practices. Factors such as better seed varieties, improved farming techniques, and favorable climatic conditions likely contribute to this upward trend. Figure 5 highlights the trends in wheat, and similar to rice and maize, wheat has also experienced a steady increase in both production and productivity from less than 1.0 in 1981 to close to 3.0 in 2020. This trend suggests that advancements in wheat cultivation techniques, such as the use of high-yield varieties and better pest control measures, have been effective. Additionally, improvements in support systems for wheat farmers, like access to fertilizers and education, may have contributed to these positive outcomes. But in contrast, Figure 6 illustrates the trends in barley and shows fluctuations in production levels, with slight overall growth from 1.0 in 1981 to 1.0 in 2020. These fluctuations suggest that barley cultivation may

LNMILLET[1]	DOLS Model
LNFERT[2]	0.0198***
	(0.0050)
LNRURALTOT[3]	0.5627**
	(0.2021)
LNTEMP[4]	-0.1985
	(0.3812)
LNCULAREA[5]	0.5832***
	(0.1064)
C	− 6.7619**
	(2.2895)
Observations	40

Table 5. Dynamic Least Squares (DOLS) regression results for millets production. The R-squared statistic is 0.9879. Standard errors are robust and reported in parentheses. Adjusted R-squared is 0.9717, S.E. of regression is 0.0140, Mean dependent var is 5.6577. S.D. dependent var 0.0831 and Sum squared residual 0.0024. ***significant at the 1 percent level, **significant at the 5 percent level. [1]Represents the natural logarithm of millet production. [2] Represents the natural logarithm of fertilizer usage. [3] Represents the natural logarithm of rural population. [4] Represents the natural logarithm of average temperature. [5] Represents the natural logarithm of cultivated area

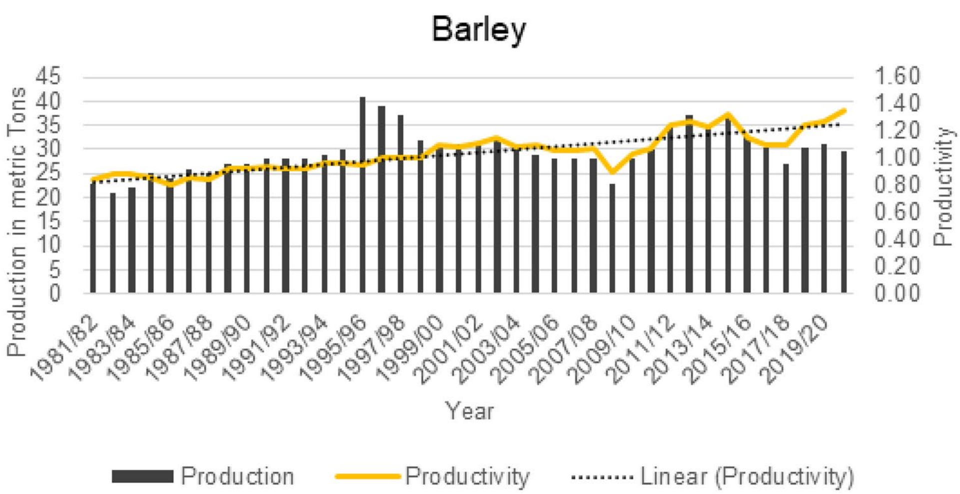

Fig. 3. Trend of Rice production and productivity.

be more susceptible to variable factors such as climate conditions and market demand. Despite these variations, the general trend is upward, indicating some level of improvement in barley farming practices and possibly adaptation to changing conditions. Similarly, Figure 7 presents the trends in millet, and unlike the other crops, millet production has remained relatively stable with minor increases in productivity from 1.0 in 1981 to 1.2 in 2020. This stability showcases millet's resilience and ability to maintain consistent output despite varying environmental and agricultural conditions. The steadiness in millet production is likely due to its adaptability to less fertile soils and harsh climates, making it a reliable crop for subsistence farming. This also suggests that little research and development has been done to improve millet productivity over the past 40 years.

Figures 3, 4, 5, 6 and 7 compares rice maize, wheat, barley, and millet production trends and productivity and emphasize substantial increases in rice, maize and wheat, but moderate growth in barley, and stagnation in millet. This comparison highlights the differing responses of these crops to advancements in agricultural practices and environmental conditions. The analysis of Figures 1 to 5 reveals that rice, maize, and wheat have experienced significant increases in both production and productivity, driven by improved agricultural techniques and better support systems. While showing overall barley and millet's stable production highlights its resilience and reliability under varying conditions, making it essential for food security in challenging environments. These trends emphasize the need for focused agricultural strategies to enhance the productivity of underutilized crops like millet based on their unique characteristics and adaptability to climate changes. Continued investment in agricultural research and development is crucial, particularly for underutilized crops like millet, which have significant potential to contribute to food security and resilience against climate change. Millet is highly

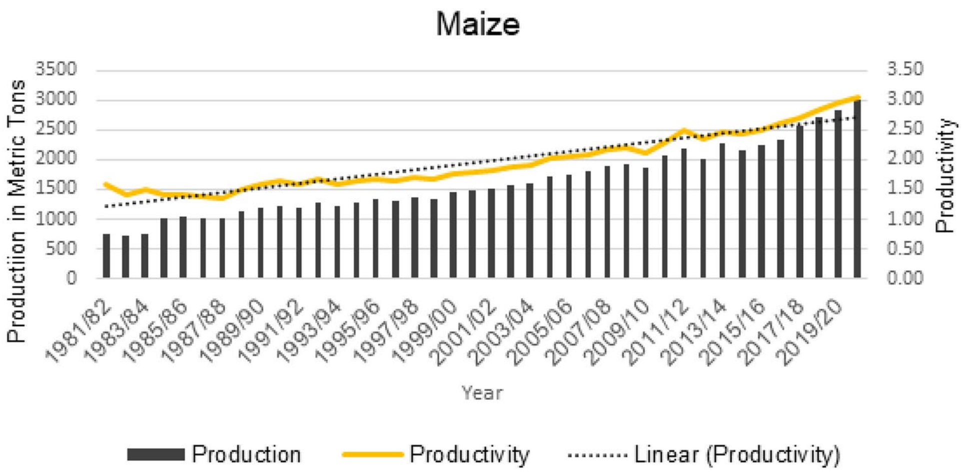

Fig. 4. Trend of Maize production and productivity.

Fig. 5. Trend of wheat production and productivity.

nutritious, with higher protein and fat content, as shown in Table 1. Millet is also better adapted to harsh environmental conditions, particularly in high-altitude regions, as indicated by the production stat shown in Table 2 Also, Figures 3, 4 and 5 demonstrate that rice, maize, and wheat have seen significant productivity gains, whereas barley and millet's stability under adverse conditions makes them reliable crops. The climatic resilience and millet's nutritional benefits highlight millet's potential to enhance food security, especially in regions vulnerable to climate change and other environmental stresses. Integrating millet into mainstream agriculture could diversify food systems and improve nutrition, making it a crucial crop for sustainable development.

To gain a comprehensive understanding of our assertion, as mentioned earlier, we analyze the trajectory of agricultural development in Nepal through the evolution of agricultural policies from 1921 to 2018. This journey across the past century mirrors a process of adaptation and transformation in response to evolving socioeconomic and environmental dynamics. Table 6 delineates this evolution, commencing with establishing the agricultural office in 1921, followed by its relocation to Singha Durbar in 1925. These initial steps signify Nepal's deliberate move towards centralized agricultural administration, advancing farming methodologies and enhancing food security. The introduction of new crop varieties, notably subtropical fruits, in 1951 and the subsequent restructuring of the Department of Agriculture in 1955 underline the nation's commitment to diversifying agricultural production and bolstering research and extension services. Between the 1960s and the 1990s, Nepal experienced a surge in development projects and national programs focused on crop intensification, farm modernization, and institutional consolidation. This period reflects heightened government intervention and external support, indicative of a concerted effort to propel agricultural growth. The pivotal integration of disparate agricultural offices into the Ministry of Agriculture in 1992 marked a significant shift towards enhanced administrative efficiency and coordination. Subsequent years witnessed the formulation of national policies, the fostering of public-private partnerships, and the initiation of agribusiness ventures, all aimed at tackling emerging challenges and leveraging opportunities in the agricultural sector. These include addressing the impacts of globalization, facilitating market liberalization, and promoting sustainable development practices.

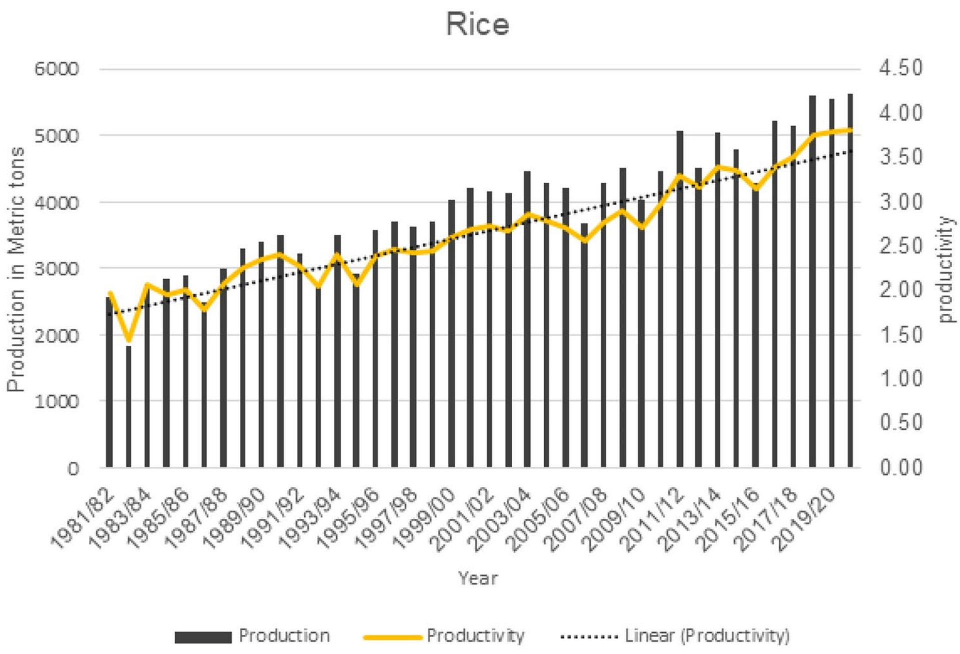

Fig. 6. Trend of barley production and productivity.

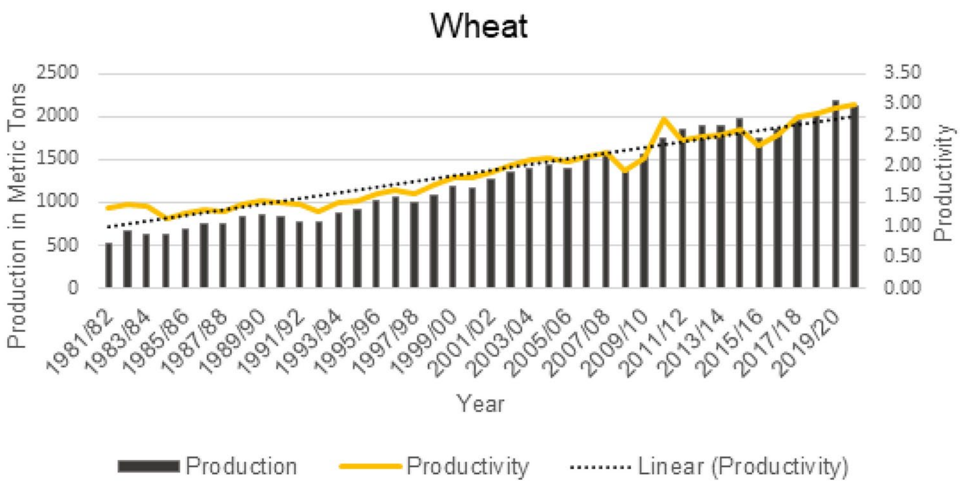

Fig. 7. Trend of millet production and productivity.

Even today, Nepal's agricultural policies remain dynamic, guided by a steadfast commitment to fostering inclusive growth, ensuring environmental sustainability, and building resilience in the face of climate change. However, there is a major issue with the focus being primarily on high-value agriculture, horticulture, and staple crops such as rice, maize, and wheat. Crops like barley and millet are often neglected or overlooked in Nepal's government's policy framework.

Figure 3, 4, 5, 6 and 7, and Tables 1, 2, 3 and 4 demonstrate that millet production has remained relatively stable over the years, even with varying climatic conditions such as temperature changes. Given this stability, it is important to explore the dynamics of millet production in more detail. Using a dynamic econometric approach, we statistically characterized this stability and modeled the relationship between millet production and key control variables, including fertilizer usage, rural population, average temperature, and cultivated areas. We employed Dynamic Least Squares (DOLS) regression to estimate the model parameters, addressing issues such as non-stationarity and endogeneity[63]. DOLS augments the cointegrating regression with leads and lags of the first differences of the regressors, effectively mitigating endogeneity concerns[64]. In our model, the dependent variable is the natural logarithm of millet production. The independent variables include the logarithms of fertilizer usage, rural population, average temperature, and cultivated area[64]. This approach allows us to understand better the factors influencing millet production and the crop's resilience to climatic variations.

Year	Program
1921	Foundation of agricultural office at Charkhal, as a regulated activity for agricultural advancement.
1925	Changed agricultural office to Department of Agriculture.
1940	Beginig of Bij Bhandar (seed storage) located at Juddha Sadak.
1947	Establishment of a Central Experimental and Research Farm at Parwanipur and an Agri farm at Kakani.
1951	Agricultural farms were built at Godavari and Kakani, and imported and planted subtropical natural products in Kakani, which was supported by the USA.
1952	For the development of a new vegetable variety in Nepal, Japanese mountaineering brought a white-neck variety of radishes.
1955	Restructuring and expansion of the Department of Agriculture into five sections: Agronomy, Horticulture, Livestock and Dairy, Agri-engineering, and Fish.
1957	Indian support mission for horticulture segment development.
1959	Foundation of Agri-farm at Janakpur, Nepalgunj, Doti.
1960	Start of cultivation advancement program (2017-2030) supported by the Indian Government.
1961	Foundation of Horticulture Centre at Kirtipur.
1962	Introduction of Horticulture Centres at Daman, Trishuli, and Baitadi.
1963	Inauguration of Horticulture Centre at Pokhara.
1964	Establishment of Khumla Agri-farm.
1966	Dissolution of the Department of Agriculture into five departments: Agriculture Expansion, Fisheries, Horticulture, Livestock, and Agriculture Education and Research.
1972	Developed two national sections: Fruits and Vegetable Department, and two national programs: Citrus and Potato Development Program.
1975	Announced as an agricultural year.
1977	Started a three-year BSc agricultural program at Agriculture and Animal Science Rampur.
1978	Initiated Coffee promotion in districts Gulmi, Palpa, and Arghakhanchi.
1981	Established the sweet orange program at Sindhuli.
1983	Started prioritized Citrus Advancement program.
1984	Started generation of Tissue refined potato seed.
1985	Announced Sindhuli and Ramechhap areas as sweet orange zones. Started 1st stage of Horticulture Development project by JICA. Foundation of Kalimati fruit and Vegetable Wholesale market.
1987	Initiated The Hill Fruit Development project in 11 areas, supported by ADB.
1990	Department of Agriculture started 20 years master plan for the development of horticulture.
1992	Promoted vegetable and fruit product improvement segments, foundation of the national tea and coffee board
1997	Ended the program supported by JICA.
2000	Developed Karnali zone agriculture development project and approved the National Tea policy.
2003	Approved the National Coffee policy.
2007	Started Lime and Onion Mission Program. Started public-private partnership program.
2009	Started the project for farming commercialization and trade in 25 districts.
2010	Developed high-value agricultural project by adopting a value chain approach for 10 years.
2012	Started public-private partnership program: One item must be produced in one district.
2013	Executed a youth-centered program for vegetable improvement.
2015	Formulated the agricultural development strategy ending in 2035.
2016	Started the Prime Minister's Agri-business modernization program for 10 years to crops such as potatoes, vegetables, citrus, etc.
2017	Celebrated the Fruit decade ending in 2027.
2018	Declared as fruit distribution year 2018.

Table 6. Historical agricultural developments in Nepal[27].

The regression results indicate that the natural logarithm of fertilizer usage (LNFERT) has a positive and statistically significant effect on millet production at the 1% level). This means that a 1% increase in fertilizer usage is associated with an approximate 0.02% increase in millet production, holding other factors fixed[47]. These results also support previous research that shows fertilizer application significantly enhances crop yields by improving soil fertility and plant nutrition. Additionally, the natural logarithm of the rural population (LNRURALTOT) has a positive and significant relationship with millet production at 5% level). The result suggests that a 1% increase in the rural population corresponds to a 0.56% increase in millet production. This relationship is likely due to the labor-intensive nature of millet cultivation, where a larger rural workforce can contribute to higher production levels. The natural logarithm of cultivated area (LNCULAREA) is significant at 1% level, indicating that a 1% increase in the cultivated area leads to an approximate 0.58% increase in millet production holding other factors fixed[57,58]. This substantial impact highlights the importance of land availability and usage in agricultural output. Expanding the area under millet cultivation could be a key strategy for increasing production and ensuring food security.

The regression analysis shows that temperature-related variables (LNTEMP) are statistically insignificant in their impact on millet production. This result suggests that, unlike other crops, millet may be resilient to temperature variations. It is possible that millet has a wider optimal temperature range or is more adaptable to fluctuations, making temperature less of a determining factor in its production. The insignificance of temperature variables suggests that millet production is relatively stable and less affected by temperature variations. This resilience, combined with the significant impact of other variables such as fertilizer usage, rural population, and cultivated area, highlights millet's potential as a reliable crop in varying climatic conditions. Unlike other crops, millet shows stable production, suggesting its robustness in adverse conditions. Millet's ability to thrive in less fertile soils and under low water availability further supports its classification as climate-resilient. The regression results also show that millet yields are less impacted by poor soil fertility and minimal rainfall, conditions that are expected to become more prevalent with ongoing climate change. This adaptability means that millet can be a reliable crop in regions that are increasingly facing soil degradation and water scarcity. The analysis indicates that rising temperatures have not significantly hindered millet production. In fact, in some cases, increasing temperatures and growing degree days (GDD) have positively impacted millet yields, as observed in central Nepal[32]. This positive response to warmer temperatures highlights millet's potential to sustain and even enhance production in the face of global warming, making it a strategic crop for future agricultural planning.

Discussion

The analysis of determinants for millet production across various Asian and African regions reveals distinct factors influencing its cultivation. In Asian countries, land ownership, irrigation, and agricultural income positively impact millet production, while factors such as distance from markets and educational levels pose challenges. For instance, subsidies and agro-based industry growth in Nepal promote millet cultivation, while high-yielding varieties and marketing preferences for other cereals hinder it. This suggests that supportive policies and market access are crucial for enhancing millet production in these regions[65]. In African countries, the determinants vary more widely Table 4 Positive influences include chemical fertilizers, household education levels, and market access, while negative factors are largely related to environmental conditions like rainfall variability. This indicates that while technical and educational interventions can boost millet production, climatic challenges remain a significant barrier. The case of Ethiopia, where chemical fertilizers have a positive impact despite variable rainfall, highlights the need for context-specific agricultural strategies.

The results show that millet is more nutritious than traditional staples such as rice and wheat. Varieties like foxtail millet and proso millet also have higher fat content, making them valuable in regions where dietary diversity and nutrition are critical. Additionally, some millet varieties have higher energy content, making them suitable as staple foods. Millet's consistent production trends, particularly in high-altitude regions of Nepal, demonstrate its resilience. While crops like maize and wheat have shown significant productivity gains due to improved agricultural practices, millet's consistent output despite environmental challenges highlights its adaptability[66]. In areas such as the western mountains of Nepal, millet's ability to thrive with minimal inputs and under harsh conditions makes it essential for food security. When compared to other major crops like maize and wheat, millet's unique advantages become evident[67]. Maize and wheat have benefited from intensive agricultural inputs and favorable climatic conditions, increasing productivity. However, these crops require optimal conditions that are not always present, especially in developing countries with variable climates[68]. In contrast, millet's ability to grow in less fertile soils and with limited water makes it a reliable food source in such environments. This resilience makes millet an invaluable crop for regions facing dietary and environmental challenges. Factors such as fertilizer use, cultivated area, and rural population significantly impact millet production, while mean temperature has a negative yet insignificant effect[69]. Millet's resilience to climate change and its nutritional benefits make it an essential crop for sustainable agriculture in the region. The stable productivity of millet, despite variable environmental conditions, emphasizes its reliability as a food source. This resilience is critical for the food security of local communities that face frequent food shortages due to the challenging terrain and climate[70]. The superior nutritional value of millet, including higher protein and fat content compared to rice and wheat, further enhances its potential to combat malnutrition and improve public health in these regions.

A comprehensive approach involving various aspects is essential to promote millet cultivation effectively. Firstly, governments should consider providing subsidies for millet seeds and fertilizers to encourage farmers, the backbone of our agricultural sector, to adopt millet cultivation. This can help offset initial costs and make millet farming more attractive. Strengthening agricultural extension services is also crucial to provide farmers with the necessary knowledge and skills to cultivate millet effectively, including training on best practices for soil management, pest control, and harvesting techniques. Another vital aspect is integrating millet into food security programs. This includes incorporating millet into school feeding programs to improve children's nutritional intake and establishing millet as a staple in emergency food reserves. Given its long shelf life and nutritional value, millet is not just an ideal crop but a crucial one for addressing food shortages during crises, underscoring the urgency and relevance of our proposal.

Furthermore, market development and consumer awareness play a significant role[71]. It is essential to develop robust market linkages to ensure that farmers have access to fair markets for selling their millet produce. This involves investing in infrastructure like roads and storage facilities[72]. Additionally, launching consumer awareness campaigns to raise awareness about the nutritional benefits of millet can help change perceptions and increase demand, particularly in urban areas where millet is often underutilized. Research and development efforts are crucial for promoting millet cultivation. Investing in research to develop and disseminate climate-resilient millet varieties that can withstand extreme weather conditions can enhance productivity and ensure food security in the face of climate change. Furthermore, supporting research into the nutritional benefits of millet and its potential health impacts is important to further promote millet as a superfood and integrate it into public health strategies.

Lastly, policy and institutional support are necessary to promote millet cultivation successfully[73]. Formulating policies that support the cultivation and consumption of millet, setting targets for millet production, and integrating millet into national food security and nutrition strategies are essential steps. Additionally, fostering collaboration between government agencies, non-governmental organizations, and international bodies can ensure comprehensive support for millet initiatives through a multi-stakeholder approach. Implementing these policy recommendations can enable millet to play a crucial role in enhancing food and nutrition security in the Himalayan foothills. Its resilience to climate change and its nutritional benefits make it an invaluable crop for sustainable development in these vulnerable regions.

Methods

This study utilizes a mixed-method approach drawing on both secondary data sources and trend analysis techniques to explore the dynamics of millet production in Nepal. Secondary data is sourced from the Food and Agriculture Organization Corporate Statistical Database (FAOSTAT) and local authorized organizations such as the Nepal Rastra Bank and the World Bank Nepal. The dataset spans approximately 30-40 years from 1981 to 2019/20 and encompasses key variables, including area, rural population, cultivated area, average temperature, and production and productivity figures for rice, wheat, maize, barley, and millet. To analyze trends, simple linear regression models are employed, facilitating the identification of overarching patterns in production and productivity. Moreover, graphical representations such as trend lines, bar graphs, and line graphs are utilized to visually elucidate the observed trends. In addition to trend analysis, the study delves into the policy landscape spanning over 50 years of agricultural development in Nepal. This historical contextualization enables a comprehensive understanding of the factors shaping agricultural outcomes over time.

To model the relationship between millet production and key control variables, a dynamic econometric approach is adopted. Specifically, we propose the following equation:

$$LNMILLET = \beta_0 + \beta_1 LNFERT + \beta_2 LNRURALTOT + \beta_3 LNTEMP + \beta_4 LNCULAREA + u$$

Where:

$$\begin{aligned} LNMILLET &: \text{represents the natural logarithm of millet production} \\ LNFERT &: \text{represents the natural logarithm of fertilizer usage} \\ LNRURALTOT &: \text{represents the natural logarithm of rural population} \\ LNTEMP &: \text{represents the natural logarithm of average temperature} \\ LNCULAREA &: \text{represents the natural logarithm of cultivated area} \\ u &: \text{error term captures unobserved factors affecting millet production not accounted} \end{aligned}$$

To estimate the parameters of this model and account for issues such as non-stationarity and endogeneity, Dynamic Least Squares (DOLS) regression is employed. DOLS augments the cointegrating regression with leads and lags of the first differences of the regressors, effectively addressing endogeneity concerns. This method has been shown to yield robust estimates even with relatively small sample sizes, making it well-suited for the empirical analysis conducted in this study. Additionally, the simplicity of implementation of DOLS is advantageous, as it does not necessitate the explicit estimation of a long-run covariance matrix.

Data availability

The dataset analyzed in the current study is publicly available online. We also attached the datasets used in this study as the supplementary file.

Received: 30 June 2024; Accepted: 30 December 2024
Published online: 25 January 2025

References

1. IFAD. The state of food security and nutrition in the world 2017. Tech. Rep., IFAD, UNICEF, and others (2017).
2. Khoury, C., Laliberté, B. & Guarino, L. Trends in ex situ conservation of plant genetic resources: a review of global crop and regional conservation strategies. *Genet. Resour. Crop Evol.* **57**, 625–639 (2010).
3. Tadele, Z. Orphan crops: Their importance and the urgency of improvement. *Planta* **250**, 677–694 (2019).
4. Chiurugwi, T., Kemp, S., Powell, W. & Hickey, L. T. Speed breeding orphan crops. *Theor. Appl. Genet.* **132**, 607–616 (2019).
5. Imathiu, S. Neglected and underutilized cultivated crops with respect to indigenous african leafy vegetables for food and nutrition security. *J. Food Secur.* **9**, 115–125 (2021).
6. Hammer, K., Heller, J. & Engels, J. Monographs on underutilized and neglected crops. *Genet. Resour. Crop Evol.* **48**, 3–5 (2001).
7. Li, X., Yadav, R. & Siddique, K. H. Neglected and underutilized crop species: the key to improving dietary diversity and fighting hunger and malnutrition in asia and the pacific. *Front. Nutr.* **7**, 593711 (2020).
8. Chivenge, P., Mabhaudhi, T., Modi, A. & Mafongoya, P. The potential role of neglected and underutilised crop species as future crops under water scarce conditions in sub-saharan africa. *Int. J. Environ. Res. Public Health* **12**, 5685–5711 (2015).
9. Andreotti, F. et al. When neglected species gain global interest: Lessons learned from quinoa's boom and bust for teff and minor millet. *Glob. Food Sec.* **32**, 100613 (2022).
10. Hossain, A. *et al.* Neglected and underutilized crop species: are they future smart crops in fighting poverty, hunger and malnutrition under changing climate? *Neglected and underutilized crops-towards nutritional security and sustainability* 1–50 (2021).
11. Saxena, R., Vanga, S. K., Wang, J., Orsat, V. & Raghavan, V. Millets for food security in the context of climate change: A review. *Sustainability***10** (2018).
12. Harish, M., Bhuker, A. & Chauhan, B. S. Millet production, challenges, and opportunities in the asia-pacific region: A comprehensive review. *Front. Sustain. Food Syst.* **8**, 1386469 (2024).
13. Vidigal, P., Romeiras, M. M. & Monteiro, F. *Sustainable crop production* (London, UK, 2019).
14. Tan, X. L. *et al.* Bambara groundnut: An underutilized leguminous crop for global food security and nutrition. *Frontiers in Nutrition*7 (2020).

15. Williams, J. T. *Global research on underutilized crops: An assessment of current activities and proposals for enhanced cooperation* (Bioversity International, 2002).
16. Wani, A. B., Biaza & Irtiza. Neglected and underutilized crops: Present status and future prospectus. *Neglected and Underutilized Crops-Towards Nutritional Security and Sustainability* 51–70 (2021).
17. Joshi, B. K., Shrestha, R. K., Ghimire, K. H., KC, H. B. & GC, A. (eds.) *Millets traditions, science and technology in Nepal* (NAGRC, CCDABC, and FAO, Kathmandu, 2023).
18. Regmi, M. *Landownership in Nepal* (University of California Press, 1966).
19. Gellner, D. N. Warriors, workers, traders and peasants: The nepali/gorkhali diaspora since the nineteenth century. In *Routledge Handbook of the South Asian Diaspora*, 136–150 (Routledge, 2014).
20. Regmi, M. C. *Regmi Research Series* (Regmi Research (Private) Ltd., Kathmandu, 1988).
21. Sapkota, B. & Joshi, B. K. Millets and their products in the nepalese markets. In Joshi, B. K., Shrestha, R. K., Ghimire, K. H., KC, H. B. & GC, A. (eds.) *Millets traditions, science and technology in Nepal*, 635–638 (NAGRC, CCDABC, and FAO, Kathmandu, 2023).
22. Bhusal, M. The historical and cultural aspects of millets. In Joshi, B. K., Shrestha, R. K., Ghimire, K. H., KC, H. B. & GC, A. (eds.) *Millets traditions, science and technology in Nepal*, 8–13 (NAGRC, CCDABC, and FAO, Kathmandu, 2023).
23. Joshi, B. K., Shrestha, R., Gauchan, D. & Shrestha, A. Neglected, underutilized, and future smart crop species in Nepal. *J. Crop Improv.* **34**, 291–313 (2019).
24. Panthi, B. Present status, importance and challenges of neglected and underutilized crops species (nucs) in nepal. *Socio Econ. Policy Stud.* **1**, 61–65 (2021).
25. Joshi, B. K. & Gauchan, D. *Agrobiodiversity, and Neglected and Underutilized Species for Food, Nutrition, Livelihood, and Environmental Security in Nepal*, 103–120 (Springer International Publishing, Cham, 2022). Edited by Timsina, Jagadish; Maraseni, Tek N.; Gauchan, Devendra; Adhikari, Jagannath; Ojha, Hemant.
26. Gauchan, D., Timsina, K. P., Gairhe, S., Timsina, J. & Joshi, K. D. *Cereal Demand and Production Projections for 2050: Opportunities for Achieving Food Self-Sufficiency in Nepal*, 19–35 (Springer International Publishing, 2022).
27. Joshi, H., Techato, K., Phoungthong, K. & Panthee, K. Determinants of millet production in Nepal. *Appl. Ecol. Environ. Res.* **21**, 3009–3023 (2023).
28. Nazneen, S. & Sultana, S. Green synthesis and characterization of cissus quadrangularis. l stem mediated zinc oxide nanoparticles. *Plant Science Archives***1** (2024).
29. Singh, B. D. et al. Millets as an ancient grains for modern food security and sustainable agriculture. *J. Sci. Res. Rep.* **30**, 706–714 (2024).
30. Pallante, G., Drucker, A. G. & Sthapit, S. Assessing the potential for niche market development to contribute to farmers' livelihoods and agrobiodiversity conservation: Insights from the finger millet case study in nepal. *Ecol. Econ.* **130**, 92–105. https://doi.org/10.1016/j.ecolecon.2016.06.017 (2016).
31. Ministry of Agricultural Development (MoALD). *Statistical Information in Nepalese Agriculture, 2021/22* (Ministry of Agricultural Development (MoALD), Kathmandu, Nepal, 2023).
32. Luitel, D. R., Siwakoti, M. & Jha, P. K. Climate change and finger millet: Perception, trend and impact on yield in different ecological regions in central Nepal. *J. Mt. Sci.* **16**, 821–835 (2019).
33. Khanal, A. P. Trend analysis of millet production and trade in nepal in order to assess its base while celebrating international year of millet 2023. *International Journal of Environmental & Agriculture Research (IJOEAR)***9**, 13 (2023).
34. Regmi, B., Kunwar, S., Acharya, T. D. & Gyawali, P. Potential of underutilized grain crops in the western mountains of Nepal for food and nutrient security. *Agriculture* **13**, 1360 (2023).
35. Amadou, I., Gounga, M. E. & Le, G.-W. Millets: Nutritional composition, some health benefits and processing - a review. *Emirates J. Food Agric.* **25**, 501–508. https://doi.org/10.9755/ejfa.v25i7.12045 (2013).
36. Volpe, S. L. Magnesium, the metabolic syndrome, insulin resistance, and type 2 diabetes mellitus. *Crit. Rev. Food Sci. Nutr.* **53**, 293–300. https://doi.org/10.1080/10408398.2010.544279 (2013).
37. Anderson, J. W. et al. Health benefits of dietary fiber. *Nutr. Rev.* **67**, 188–205. https://doi.org/10.1111/j.1753-4887.2009.00189.x (2009).
38. Vali Pasha, K. *et al.* Proximate, mineral composition and antioxidant activity of traditional small millets cultivated and consumed in rayalaseema region of south india. *J. Sci. Food Agric.***98**, 652–660, https://doi.org/10.1002/jsfa.8510 (2018).
39. Gauchan, D. Survey of the status of traditional underutilized food crops - future smart food - for food and nutrition security in the mountains of nepal (2020). Manuscript.
40. Tiwari, H. et al. Underutilized nutrient rich millets: Challenges and solutions for India's food and nutritional security: A review. *Int. J. Plant Soil Sci.* **35**, 45–56 (2022).
41. Adhikari, R. Economics of finger millet (elecusine coracana g.) production and marketing in peri-urban area of pokhara valley of Nepal. *J. Dev. Agric. Econ.***4** (2012).
42. Nations, U. Global hunger numbers rose to as many as 828 million in 2021. – un report (2022). Food and Agriculture Organization of the United Nations.
43. Ladha, J. K., Pathak, H., J. Krupnik, T., Six, J. & van Kessel, C. *Efficiency of Fertilizer Nitrogen in Cereal Production: Retrospects and Prospects*, 85–156 (Elsevier, 2005).
44. Hayashi, K., Abdoulaye, T., Gerard, B. & Bationo, A. Evaluation of application timing in fertilizer micro-dosing technology on millet production in Niger, West Africa. *Nutr. Cycl. Agroecosyst.* **80**, 257–265 (2007).
45. Eyshi Rezaei, E., Gaiser, T., Siebert, S., Sultan, B. & Ewert, F. Combined impacts of climate and nutrient fertilization on yields of pearl millet in Niger. *Eur. J. Agronomy* **55**, 77–88 (2014).
46. Sharma, V., Pandey, R. & Sharma, B. Studies on long term impact of stcr based integrated fertilizer use on pearl millet (pennisetum glaucum)-wheat (triticum aestivum) cropping system in semi arid condition of india. *J. Environ. Biol.* **36**, 241 (2015).
47. Bewket, W. Rainfall variability and crop production in ethiopia: Case study in the amhara region. In *Proceedings of the 16th international conference of Ethiopian studies*, vol. 3, 823–836 (Norwegian University of Science and Technology Trondheim, Norway, 2009).
48. Maharjan, K. L. & Joshi, N. P. Effect of climate variables on yield of major food-crops in nepal: A time-series analysis. *Climate change, agriculture and rural livelihoods in developing countries* 127–137 (2013).
49. Nelson, W., Hoffmann, M., Vadez, V., Roetter, R. & Whitbread, A. Testing pearl millet and cowpea intercropping systems under high temperatures. *Field Crop Res.* **217**, 150–166 (2018).
50. Karim, A., Abukari, A.-B. T. & Abdulai, A.-M. Testing the climate resilience of sorghum and millet with time series data. *Cogent Food Agric.***8** (2022).
51. Gitu, G. W., Onyango, C. & Obara, J. Selected factors affecting adoption of improved finger millet varieties by small-scale farmers in the semi-arid mogotio district, kenya. *Int. J. Sci.: Basic Appl. Res.* **13**, 448–465 (2014).
52. Handschuch, C. & Wollni, M. Improved production systems for traditional food crops: The case of finger millet in Western Kenya. *Food Secur.* **8**, 783–797 (2016).
53. Mukhtar, U., Mohamed, Z., Shamsuddin, M., Sharifuddin, J. & Muktar, B. An assessment of socio-economic determinants of pearl millet production in northwestern Nigeria: An ordinary least square analysis. *Asian J. Soc. Sci. Humanities* **7**, 1 (2018).
54. Liu, L., Xu, X. & Chen, X. Assessing the impact of urban expansion on potential crop yield in China during 1990–2010. *Food Secur.* **7**, 33–43 (2015).

55. Song, S., Liu, Z., He, C. & Lu, W. Evaluating the effects of urban expansion on natural habitat quality by coupling localized shared socioeconomic pathways and the land use scenario dynamics-urban model. *Ecol. Ind.* **112**, 106071 (2020).
56. Bhatt, D. et al. Nutritional advantages of barnyard millet and opportunities for its processing as value-added foods. *J. Food Sci. Technol.* **60**, 2748–2760 (2023).
57. Ma, K. et al. The relationship between ecological factors and commercial quality of high-quality foxtail millet "jingu 21". *Food Res. Int.* **163**, 112225 (2023).
58. Lubadde, G., Tongoona, P., Derera, J. & Sibiya, J. Production determinants of the pearl millet cropping system in Uganda and implications to productivity. *J. Agric. Sci.* **8**, 97 (2016).
59. Gebreyohannes, A. et al. Finger millet production in Ethiopia: Opportunities, problem diagnosis, key challenges and recommendations for breeding. *Sustainability* **13**, 13463 (2021).
60. of Plant Genetic Resources, I. S. Indian society of plant genetic resources. *Indian Journal of Plant Genetic Resources***25** (2012).
61. Gyawali, P. Production trend, constraints, and strategies for millet cultivation in Nepal: A study from review perspective. *Int. J. Agric. Appl. Sci.* **2**, 30–40 (2021).
62. Abdallah, M. *Determinants for local pearl millet consumption in Singida rural and Kishapu districts*. Ph.D. thesis, Sokoine University of Agriculture (2013).
63. Abbas, S. Climate change and major crop production: Evidence from Pakistan. *Environ. Sci. Pollut. Res.* **29**, 5406–5414 (2021).
64. Kumar, P., Sahu, N. C., Kumar, S. & Ansari, M. A. Impact of climate change on cereal production: Evidence from lower-middle-income countries. *Environ. Sci. Pollut. Res.* **28**, 51597–51611 (2021).
65. Mabhaudhi, T. et al. Prospects of orphan crops in climate change. *Planta* **250**, 695–708 (2019).
66. Mottaleb, K. A., Rahut, D. B., Kruseman, G. & Erenstein, O. Wheat production and consumption dynamics in an Asian rice economy: The Bangladesh case. *Eur. J. Dev. Res.* **30**, 252–275 (2018).
67. Kalli, R. et al. Effect of irrigation on farm efficiency in tribal villages of eastern India. *Agric. Water Manag.* **291**, 108647 (2024).
68. Tanti, P. C., Jena, P. R., Timilsina, R. R. & Rahut, D. B. Enhancing crop yields and farm income through climate-smart agricultural practices in Eastern India. *Mitig. Adapt. Strat. Glob. Change* **29**, 35 (2024).
69. Ali, A., Rahut, D. B. *et al.* Healthy foods as proxy for functional foods: consumers' awareness, perception, and demand for natural functional foods in Pakistan. *Int. J. Food Sci.***2019** (2019).
70. Gebre, G. G., Amekawa, Y. & Rahut, D. B. Improved maize technology adoption and its intensity among male-and female-headed households in Dawuro zone, southwestern ethiopia. *Gend. Technol. Dev.* **27**, 42–59 (2023).
71. Mottaleb, K. A., Rahut, D. B., Kruseman, G. & Erenstein, O. Changing food consumption of households in developing countries: A Bangladesh case. *J. Int. Food Agribusiness Market.* **30**, 156–174 (2018).
72. Dash, M. et al. Determinants of household collection of non-timber forest products (ntfps) and alternative livelihood activities in similipal tiger reserve, india. *Forest Policy Econ.* **73**, 215–228 (2016).
73. Ma, W., Marini, M. A. & Rahut, D. B. Farmers' organizations and sustainable development: An introduction. *Ann. Public Cooperative Econ.* **94**, 683–700 (2023).
74. Oladimeji, Y. U., Offokans, C. C. & Egwuma, H. Analysis of economic efficiency and its determinants in millet based production systems in the derived savanna zone of nigeria. *Alanya Akademik Bakis* **5**, 177–192 (2021).
75. Muthamilarasan, M., Dhaka, A., Yadav, R. & Prasad, M. Exploration of millet models for developing nutrient rich graminaceous crops. *Plant Sci.* **242**, 89–97 (2016).
76. Kumar, S. *et al.* Small millets: A multifunctional crop for achieving sustainable food security under climate change. *Plant Sci. Today* [SPACE] https://doi.org/10.14719/pst.4113 (2024).

Acknowledgements

We would like to thank the Asian Development Bank Institute (ADBI) for its support. Views expressed in this paper do not reflect the view of the author's institution, and the usual disclaimer applies. This map does not imply the expression of any opinions of the authors or the author's institution concerning the boundaries.

Author contributions

R.R.T, H. P.J and D.B.R designed the research and R.R.T and H. P. J performed the data collection and analysis. R.R.T, H. P.J and D.B.R analyzed the results, and R.R.T, H. P.J and D.B.R wrote the original manuscript. All authors reviewed the manuscript.

Declarations

Competing interests

The authors declare no competing interests.

Ethical approval

Data used in this study is publicly available. It does not involve human subjects, and is not based on a survey or experiment. Further, the data is at the district level, and not at the individual or household level.

Informed consent

This study uses secondary data and is not based on a survey or experiment.

Human and animal rights

This study uses secondary data publicly available at the district level.

Additional information

Correspondence and requests for materials should be addressed to R.R.T.