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A Blueprint for Building Resilience and Food Security in MENA and SSA Drylands: Diversifying Agriculture With Neglected and Underutilized Species

Krishna Prasad Devkota[1] | Mina Devkota[1] | Tafadzwanashe Mabhaudhi[2,3,4] | Vinay Nangia[1] | Samar Attaher[5] | Ruhiza Jean Boroto[6] | Jagadish Timsina[7] | Kadambot H. M. Siddique[8]

[1]International Center for Agricultural Research in the Dry Areas (ICARDA), Rabat, Morocco | [2]Centre on Climate Change, London School of Health and Tropical Medicine, London, UK | [3]Centre for Transformative Agricultural and Food Systems, School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal, Pietermaritzburg, South Africa | [4]United Nations University: Institute for Water, Environment and Health (UNU-INWEH), Richmond Hill, Ontario, Canada | [5]International Center for Agricultural Research in the Dry Areas (ICARDA), Cairo, Egypt | [6]Land and Water Division, Food and Agriculture Organization (FAO-NSL), Rome, Italy | [7]International Fertilizer Development Center (IFDC), Muscle Shoals, Alabama, USA | [8]The UWA Institute of Agriculture, The University of Western Australia, Perth, Western Australia, Australia

Correspondence: Krishna Prasad Devkota (k.devkota@cgiar.org)

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ABSTRACT

Drylands, encompassing 41% of global land and supporting over 2 billion people, face significant challenges, including water scarcity, extreme temperature events, and soil degradation. Dryland spans vast areas of Middle East and North Africa (MENA) and Sub-Sahara Africa (SSA) regions and poses a threat to food security and resilience. This study examines the potential of neglected and underutilized species (NUS) to improve dryland food and nutrition security, focusing on their agronomic performance, water productivity, economic viability, and nutritional benefits. Using long-term data from FAOSTAT, USDA Food Data Central, and peer-reviewed literature, we analyzed trends in the cultivation, yield, and nutritional contributions of 21 NUS across 22 countries in the MENA region comparing them with major staples—rice, wheat, and maize. Between 1961 and 2022, NUS areas in MENA fluctuated, decreasing by 7.0% since 2018 to 21.17 Mha. Despite this, NUS demonstrated superior water productivity—up to 30% higher than major cereals. For instance, sorghum and cowpea achieved 2.5 kg/m^3 compared to maize (0.83 kg/m^3) and wheat (0.91 kg/m^3) and exhibited strong heat tolerance, withstanding temperatures of up to 42°C and 38°C, respectively. Despite a negative trade balance, NUS significantly contributed to dietary calories, surpassing wheat. A field experiment in Merchouch, Morocco, confirmed that NUS offered a higher economic and nutritional values per unit than wheat, and outperformed conventional crops across key indicators. Integrating NUS into dryland farming systems enhance food security, sustainability, and resilience to climate change. Advancing NUS requires breeding programs, tailored good agricultural practices, value addition and market linkage, incentivization policies, and farmer education. Collaborative efforts among international organizations, governments, and civil society are crucial to mainstreaming NUS in agrifood systems and contributing to the diversity, sustainability, and resilience of dryland farming systems in MENA and SSA regions.

1 | Introduction

Dryland ecosystems, which cover 41% of the Earth's surface and support over 2.5 billion people (Gaur and Squires 2018), are crucial for global food security. However, these regions—particularly in the Middle East and North Africa (MENA), Central and West Asia, and sub-Saharan Africa (SSA)—face pressing challenges such as water scarcity, extreme temperatures, and soil degradation. These issues threaten agricultural productivity, making it essential to develop sustainable farming systems that can maintain food production while conserving natural resources and adapting to climate change (Dawson et al. 2019; Morton 2007; Ndlovu et al. 2024; Palombi and Sessa 2013).

Neglected and underutilized species (NUS) are gaining recognition for their potential to address some of these challenges in dryland agriculture (Chivenge et al. 2015; Mabhaudhi et al. 2019; Meldrum and Padulosi 2017; USDA 2024). Often referred to as "orphan," "abandoned," or "niche" crops; NUS are well suited to marginal environments and are crucial for enhancing food security, promoting biodiversity, and supporting sustainable agricultural practices (Mabhaudhi et al. 2019; Padulosi, Thompson, and Rudebjer 2013; Siddique, Li, and Gruber 2021; Yang et al. 2024). Despite their adaptability and resilience to climate change, NUS have historically received little attention in agricultural research, policy frameworks, and development initiatives (Mabhaudhi et al. 2018; Ndlovu et al. 2024; Popoola et al. 2019; Sharma et al. 2022).

NUS species encompass cereal, legume, fruit, vegetable, and root crops, typically adapted to local conditions and cultural preferences. These species are vital for several reasons: (1) They enhance dietary diversity and nutritional security by providing essential nutrients, vitamins, and minerals often lacking in staple crops like rice, wheat, and maize (Akram, Layla, and Ismail 2023; Chivenge et al. 2015). For example, amaranth, millet, and quinoa are rich in micronutrients such as iron and zinc, critical for addressing malnutrition in vulnerable populations (Dawson et al. 2019; Mudau et al. 2022). (2) NUS are often sources of unique bioactive compounds with health benefits, such as antioxidant, anti-inflammatory, and anticarcinogenic properties (Mabhaudhi et al. 2019; Taaime et al. 2023). (3) These species are well suited to marginal environments, where major crops struggle, providing a reliable food source and supporting smallholder farmers in arid and semi-arid regions (Agoud and Mabrouki 2024; Meena et al. 2024). For instance, drought-tolerant sorghum thrives in these regions, withstanding temperatures up to 42°C, achieving superior water productivity, making it a key crop where water is scarce (Hadebe, Modi, and Mabhaudhi 2017; Palombi and Sessa 2013; Yang et al. 2024). (4) Integrating NUS into farming systems enhances agricultural biodiversity, resilience, and stability, critical for adapting to climate variability and conserving natural resources (Kencharaddi et al. 2024; Matías et al. 2024). NUS are often stigmatized as "food for the poor" resulting in their underutilization (Mabhaudhi et al. 2019; Ndlovu et al. 2024).

In dryland ecosystems, agricultural biodiversity is crucial for resilience and stability. Initiatives such as the FAO's "Future Smart Food" emphasize the importance of NUS in enhancing food security, climate resilience, and sustainable agriculture (Siddique and Li 2019). Moreover, as underscored by Ndlovu et al. (2024), NUS support food sovereignty by empowering marginalized communities, especially women, to maintain traditional food systems and reduce reliance on imported staples. Recent research highlights the significant carbon and water efficiency advantages of cultivating NUS, particularly in the MENA region, where environmental stressors are more severe (Agoud and Mabrouki 2024). For example, integrating quinoa, cowpea, and lentils into dryland farming systems improves water use efficiency (WUE), reduces greenhouse gas (GHG) emissions, enhances resilience to climate variability, improves soil health, and increases biodiversity (Mustafa, Mabhaudhi, and Massawe 2021; Mabhaudhi et al. 2018). Moreover, NUS cultivation offers significant economic benefits. Many NUS, such as sesame and millet, have higher market values per unit than staple crops like wheat and maize, offering economic incentives for farmers to diversify their cropping systems (Dawson et al. 2019; Siddique and Li 2019).

Despite these advantages, several barriers hinder the widespread adoption of NUS in mainstream agriculture, including limited awareness among farmers and consumers, insufficient research and development (R&D), and policy frameworks that prioritize major staple crops over NUS (Choukr-Allah et al. 2016; Padulosi, Thompson, and Rudebjer 2013). Overcoming these barriers requires coordinated efforts to promote NUS through enhanced research, extension services, and supportive policies (Mabhaudhi et al. 2017; Taaime et al. 2023). This study seeks to address gaps in understanding the role of NUS in food security, focusing on their caloric contribution, nutrient density, and water productivity in dryland regions like MENA and SSA. The study aims to unlock the full potential of NUS for sustainable agriculture and food security in the MENA and SSA regions by (a) assessing the current status and trends of NUS, (b) identifying key challenges and opportunities for their cultivation and commercialization, (c) evaluating their nutritional and ecological benefits, and (d) developing recommendations to enhance research, policy support, and market access for their promotion.

2 | Materials and Methods

2.1 | Study Area and Crops

The study focuses on 22 countries in the MENA region: Algeria, Bahrain, Egypt, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Libya, Mauritania, Morocco, Oman, Palestine, Qatar, Saudi Arabia, Somalia, Sudan, Syria, Tunisia, United Arab Emirates, and Yemen (Figure 1). These countries span a range of semi-arid, arid, predesertic, and desertic climates, characterized by varying temperature and rainfall patterns.

Major NUS are presented in Table 1. The 21 NUS selected for this study due to their adaptability to arid environments and their potential to enhance food security and biodiversity in the MENA region include bean (*Phaseolus vulgaris*), cassava (*Manihot esculenta*), chickpea (*Cicer arietinum*), cowpea (*Vigna unguiculata*), faba bean (*Vicia faba*), groundnut/peanut (*Arachis hypogaea*), lentil (*Lens culinaris*), linseed (*Linum usitatissimum*), lupin (*Lupinus* spp.), millet (*Panicum miliaceum*—Proso millet; *Pennisetum glaucum*—pearl millet; and *Eleusine coracana*—finger millet), oat (*Avena sativa*), rapeseed (*Brassica napus*), safflower (*Carthamus tinctorius*), sesame (*Sesamum indicum*), sorghum (*Sorghum bicolor*), sugar beet (*Beta vulgaris*),

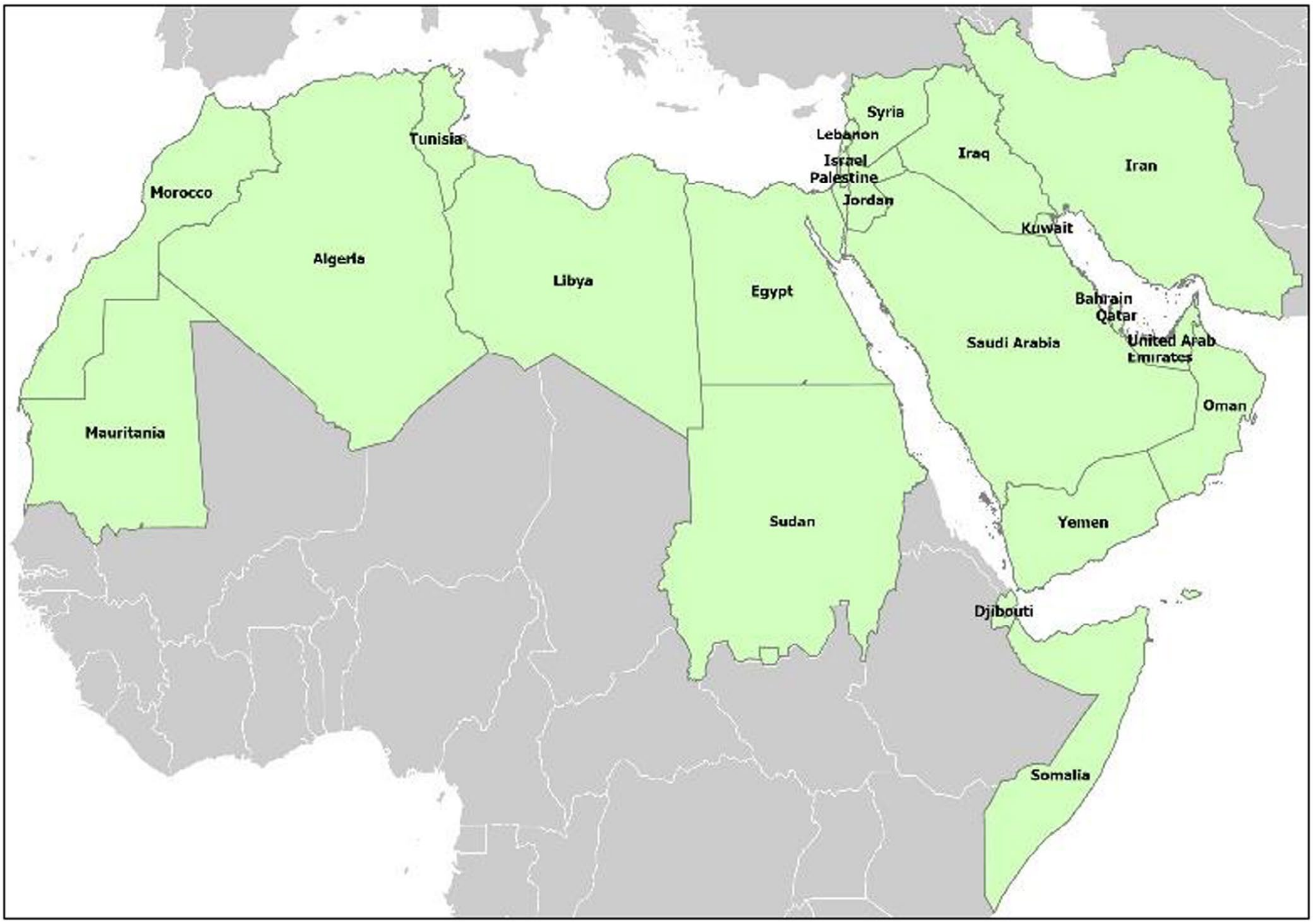

FIGURE 1 | Countries of Middle East and North Africa (MENA) region included in the study.

sunflower (*Helianthus annuus*), sweet potato (*Ipomoea batatas*), taro (*Colocasia esculenta*), triticale (× *Triticosecale*), and yam (*Dioscorea* spp., commonly *Dioscorea alata* and *Dioscorea rotundata*). Dry beans, lentils, groundnut, sugarbeet, and sunflower are categorized as NUS in the MENA region due to limited research, development, and investment compared to major staples like wheat and barley. Crops like barley, durum wheat, olive, date palm, soybean, moringa, teff, cactus, digitaria, and strawberry—considered NUS in other regions—were excluded from this study due to their widespread cultivation in the MENA region.

2.2 | Literature Review

A comprehensive literature review was conducted to gather water productivity and heat tolerance data and identify research gaps and innovations related to NUS. Sources included peer-reviewed journals, books, reports from international organizations such as FAO and the CGIAR portal, and publications from agricultural research institutions. Research gaps were identified through a systematic literature review and expert consultations. The studies were screened for recurring themes, overlooked areas, and inconsistencies. The results are categorized and summarized in Table 3, with insights from the authors incorporated to ensure a comprehensive analysis of critical research gaps.

2.3 | Primary Data From Field Experiments

Field experiments were conducted in the 2019/20 and 2020/21 growing seasons in Merchouch, Morocco to compare the yield, production costs, and water application efficiency of three cropping systems: lentil, lentil + chickpea, and lentil + quinoa relay intercropping compared with sole wheat. The crops were sown in November and harvested in May-July. Recommended seed and fertilizer rates were used for each crop. In relay intercropping, intercrops were planted at the flowering time of the main crop. Details has been presented in Devkota and Nangia (2022). Key parameters measured included calorie and protein yields, following wheat crop yield, production costs, gross margins, rainfall WUE, and GHG emissions intensity (GHGI), using methodology outlined by Devkota et al. (2021, 2022a).

2.4 | Secondary Data

Secondary data were obtained from FAOSTAT, the USDA FoodData Central database (https://fdc.nal.usda.gov/), and national agricultural statistics from MENA countries. Data spanning 1961–2022 were analyzed, covering trends in area, yield, import/export quantities, nutritional (calorie) values of NUS, and major staples like wheat, rice, and maize.

TABLE 1 | Major neglected and underutilized species by crop type, production environment, and their significance.

Crop	Region	Production environment	Significance
I. Cereals and grains			
Sorghum	Africa, Asia, MENA	Arid, semi-arid	Drought-resistant staple; used as food, fodder, and biofuel
Pearl millet	Africa, South Asia	Arid, sandy soils	Thrives in low-fertility soils; rich in zinc and iron
Finger millet	Africa, South Asia	Rocky and shallow soils	High calcium content; resilient to drought and poor soils
Foxtail millet	East Asia, MENA	Marginal, degraded soils	Adapted to saline and nutrient-deficient conditions
Teff	East Africa	High-altitude, well-drained soils	Gluten-free cereal; staple in Ethiopian diets
Quinoa	Andes, MENA	Saline, marginal soils	Grows in salty soils; rich in protein and amino acids
Proso millet	Europe, Asia	Cold, semi-arid	Short growing season; thrives in water-limited regions
Fonio	West Africa	Sandy, nutrient-poor soils	Highly drought-resistant cereal; rich in amino acids
Kodo millet	South Asia	Marginal soils	Hardy and nutrient-dense cereal; rich in dietary fiber
Amaranth	Africa, Latin America	Tropical, semi-arid	Leafy vegetable and grain; rich in iron and protein
Wild rice	North America, Asia	Wetlands, marshy areas	Protein- and antioxidant-rich
Barnyard millet	South Asia, East Asia	Marginal soils, semi-arid	Short-cycle crop; excellent for degraded environments
Barley	MENA, Central Asia	Arid, semi-arid	Staple food and forage crop; thrives under low rainfall conditions
Durum wheat	MENA, Mediterranean Basin	Semi-arid, drylands	Used for pasta and couscous; drought-tolerant
Kamut (Khorasan wheat)	MENA, Mediterranean Basin	Arid, nutrient-poor soils	Ancient wheat variety; rich in protein and antioxidants; grows in drylands
Triticale	MENA, Europe	Marginal, degraded soils	Hybrid of wheat and rye; grows well in poor soils and arid climates
Einkorn wheat	MENA, Mediterranean Basin	Semi-arid, hilly terrains	Ancient wheat species; highly tolerant to drought and adapted in marginal conditions
II. Legume and pulses			
Cowpea	Africa, Asia	Arid, semi-arid	Protein rich; fixes nitrogen; grows in water-scarce regions
Chickpea	South Asia, MENA, East Africa	Semi-arid, well-drained soils	Highly water efficient; improves soil fertility through nitrogen fixation
Lentil	MENA, South Asia	Marginal, semi-arid	Drought-tolerant legume; rich in protein and iron

(Continues)

TABLE 1 | (Continued)

Crop	Region	Production environment	Significance
Bambara groundnut	Africa, Southeast Asia	Sandy, nutrient-poor soils	Thrives in low-input farming systems; highly drought tolerant
Pigeon pea	SSA, Asia	Tropical, semi-arid	Heat- and drought-tolerant legume; suitable in intercropping systems
Winged bean	Southeast Asia	Humid, low-fertility soils	Multipurpose legume; rich in protein and essential vitamins
Velvet bean	Asia, Africa	Marginal soils	Used for green manure; nitrogen-fixing properties improve soil fertility
Cluster bean	South Asia, Africa	Arid, saline soils	Source of guar gum; grows in hot, dry climates
Lablab bean	Africa, Asia	Poor, well-drained soils	Dual-purpose legume for food and fodder; drought adapted
Marama bean	Southern Africa	Arid regions	Protein-rich crop; grows in harsh desert conditions
Grass pea	MENA, South Asia	Marginal, semi-arid	Drought-tolerant legume; grows in low-input systems; high protein content
Acacia pods	MENA, Sahel	Arid, semi-arid	Edible pods and seeds; used as fodder and food during droughts
III. Tubers and root crops			
Cassava	SSA, South America	Marginal, nutrient-poor soils	High-calorie crop; thrives in drought-prone areas
Sweet potato	SSA, Asia	Marginal, semi-arid	Beta-carotene–rich tuber; highly drought-tolerant
Yam	West Africa, Caribbean	Tropical, humid zones	Staple food in tropical areas; high market value
Taro	Pacific Islands, MENA	Waterlogged and saline soils	Versatile tuber crop; vital in traditional diets
Ulluco	Andes	High-altitude, poor soils	Colorful, nutrient-rich tubers; adapted to cold climates
Ensete	Ethiopia	High-altitude, semi-arid	Food reserve crop; key during famine periods
Arrowroot	Asia, Latin America	Humid, marginal soils	Starch rich; used in food and traditional medicine
Cocoyam	West Africa, Pacific	Humid, tropical zones	High in carbohydrates; thrives in poorly drained soils
Ahipa (Andean yam bean)	Andes	Semi-arid, well-drained soils	Protein-rich tuber; resilient to nutrient-poor environments
Tiger nut	Africa, Europe	Arid, saline soils	Used for oil, snacks, and beverages; drought tolerant
IV. Fruits			
Date palm	MENA	Arid, extreme heat	Key calorie source; thrives in desert conditions

(Continues)

TABLE 1 | (Continued)

Crop	Region	Production environment	Significance
Baobab	Africa	Arid, semi-arid	Rich in vitamin C; used in beverages and traditional medicine
Pitaya (dragon fruit)	Asia, Latin America	Arid, semi-arid	Drought-adapted fruit crops; rich in antioxidants
Jujube	MENA, Asia	Marginal, saline soils	Hardy fruit tree; valued for medicinal and nutritional benefits
Camu camu	South America	Nutrient-poor, flood-prone zones	Superfood rich in vitamin C; adapted to tropical wetlands
Lucuma	Andes	High-altitude, dry areas	Sweet fruit; nutrient dense with antioxidant properties
Cactus pear (Nopal)	Latin America, MENA	Arid, saline	Hardy fruit and fodder crop; drought tolerant
Ackee	Caribbean	Tropical, saline	High-value tropical fruit; used in traditional dishes and as an oil source
Horned melon	Africa	Arid, drought prone	Nutrient-dense fruit with unique flavor; thrives in degraded soils
Olive	MENA, Mediterranean Basin	Arid, Saline soils	Multipurpose tree; produces oil and thrives in drought-prone areas
Pomegranate	MENA, South Asia	Arid, semi-arid	Hardy fruit crop; valued for its juice and medicinal properties
Carob	MENA, Mediterranean Basin	Arid, nutrient-poor soils	Legume tree-producing pods; used for syrup, fodder, and food
V. Forage and multipurpose trees			
Moringa (Drumstick tree)	Africa, South Asia	Arid, semi-arid	Nutrient-dense leaves and pods; used for food, fodder, and water purification
Leucaena	Asia, Africa	Semi-arid, degraded lands	Nitrogen-fixing tree; valued for fodder and agroforestry
Napier grass	SSA	Tropical, humid	Drought-tolerant fodder crop; high biomass production
Sesbania	Asia, Africa	Wetlands, degraded lands	Multipurpose tree for soil improvement, fodder, and fuelwood
Atriplex (Saltbush)	MENA, Australia	Saline, arid soils	Forage crop for livestock; highly salt and drought tolerant
Halophytes	MENA, Asia	Coastal, saline soils	Used for forage in degraded lands; highly salt-tolerant species

Cultivation areas in various countries were calculated and compared for each NUS over the 1961–2022 period. Import and export data for NUS and wheat crops were analyzed, and the trade balance for each crop (FAOSTAT data) was calculated as:

$$\text{Trade balance (amount and value)} = \text{Total exports} - \text{Total imports} \quad (1)$$

A positive trade balance indicates a net exporter, while a negative value indicates a net importer.

The calorie contribution of each crop was computed by multiplying the amount produced by its calorie content derived from USDA FoodData:

$$\text{Total calorie contribution (kcal)} = \text{Quantity produced} \times \text{Caloric content per 100 g} \quad (2)$$

Water application rates for each crop were sourced from Brouwer and Heibloem (1986). Water productivity was calculated using crop yield data (FAOSTAT 2024) and water use:

$$\text{Water productivity}\left(\text{kg grain per m}^3\text{ water}\right) = \frac{\text{Crop yield (kg)}}{\text{Water use}\left(\text{m}^3\right)} \quad (3)$$

Higher water productivity indicates more efficient water use.

2.5 | Statistical Analysis

Descriptive statistics, trend analyses, and mean percentages were calculated using Excel and SigmaPlot. Secondary data were aggregated by year, region, and crop type. Inferential statistics, such as regression and time-series analysis, were applied as appropriate. Multicriteria decision analysis evaluated trade-offs between indicators like yield, nutrient content, economic profitability, WUE, and GHG emissions. These indicators were normalized and weighted for comparative analysis, identifying potential crop synergies and trade-offs.

3 | Results

3.1 | Assessment of Current Status and Trends of NUS

3.1.1 | NUS Areas Compared to Staple Cereals in MENA and SSA

Figure 2 illustrates the extensive area dedicated to NUS compared to major cereals like rice, wheat, and maize in 2022. NUS cover approximately 363.1 Mha globally, surpassing wheat (219.2 Mha), maize (204.6 Mha), and rice (165.0 Mha), underscoring their global importance. In Asia, rice dominates with 142.0 Mha, followed by wheat (89.1 Mha) and maize (68.2 Mha), while NUS occupy 80.2 Mha. In SSA, NUS cover 139.9 Mha, showcasing their crucial role in food security, compared to maize (41.1 Mha), rice (15.8 Mha), and wheat (3.3 Mha). In the MENA region, NUS span 21.2 Mha, outpacing wheat (15.2 Mha), maize (1.5 Mha), and rice (1.1 Mha), highlighting their potential for addressing food security in arid and semi-arid regions. Key NUS in the MENA region include sorghum, sesame, groundnut, and millet, occupying 16.65 Mha. In SSA, major NUS such as sorghum, cassava, millet, groundnut, cowpea, yam, cocoa bean, dry beans, sesame, plantain, and sweet potato account for 151 Mha.

3.1.2 | NUS Areas Comparison in MENA Countries

Figure 3 shows the long-term cultivation trends (1961–2022) of 21 NUS across 22 MENA countries. While the total area for NUS has increased since 1961, there has been a 7.0% decline in the last 5 years, from 22.52 Mha in 2018 to 21.1 Mha in 2022. Several crops experienced significant decreases, with millet showing the greatest reduction (from 3.87 to 2.62 Mha; −32%), followed by sorghum (from 8.99 to 7.99 Mha; −11%), chickpea (from 0.61 to 0.58 Mha; −6%), faba bean (from 0.39 to 0.31 Mha; −21%), lentil (from 0.22 to 0.21 Mha; −11%), and groundnut (from 3.16 to 3.10 Mha; −2.0%).

3.1.3 | Country Comparison of NUS in MENA

Figure 4 provides a country-specific analysis of NUS areas from 1961 to 2022 in MENA countries, showing significant variability. The total area fluctuated from 3.63 Mha in 1961 to 22.74 Mha in 2018 before declining. With no recorded NUS area until 2011, Sudan increased from 8.18 Mha in 2012 to 18.84 Mha in 2018 before declining by 8% from 2018 to 2022. Iran increased from 0.27 Mha in 1961 to 1.50 Mha in 1992, fluctuating in subsequent years until peaking at 1.62 Mha in

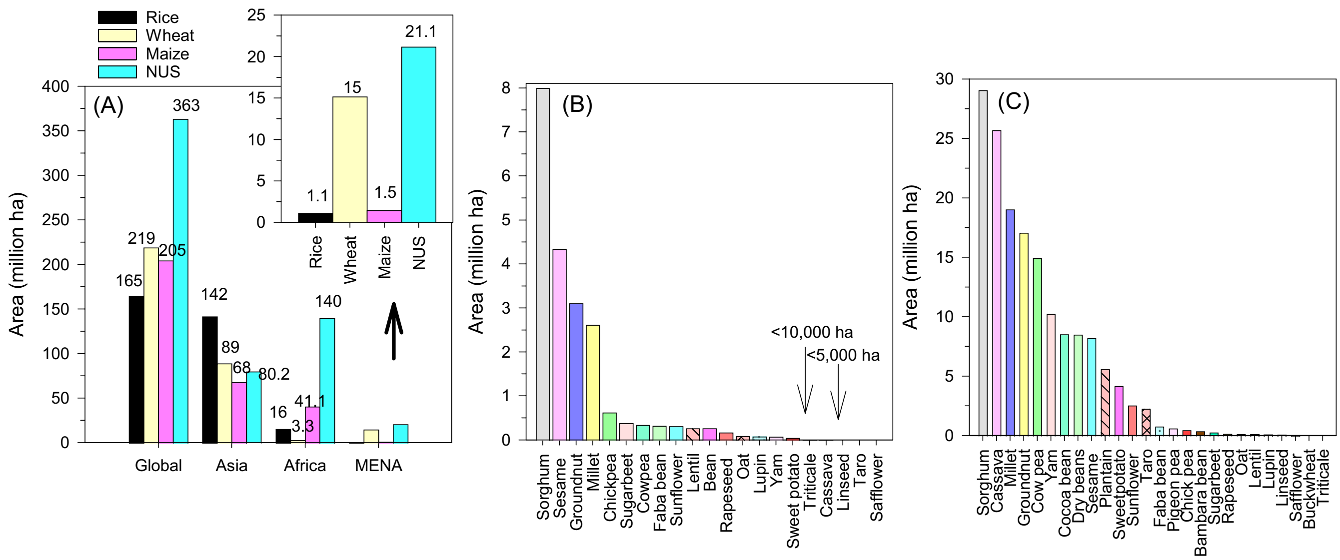

FIGURE 2 | (A) Area distribution of 21 (crops of Fig. B) major neglected and underutilized (NUS) areas compared to three major cereals in the Middle East and North Africa (MENA) region with Global, Asian, and African comparisons, (B) the distribution of 21.17 Mha among 21 NUS in the MENA region, and (C) 159.3 Mha area among 26 NUS in Sub-Saharan Africa (*Data source:* FAOSTAT 2024).

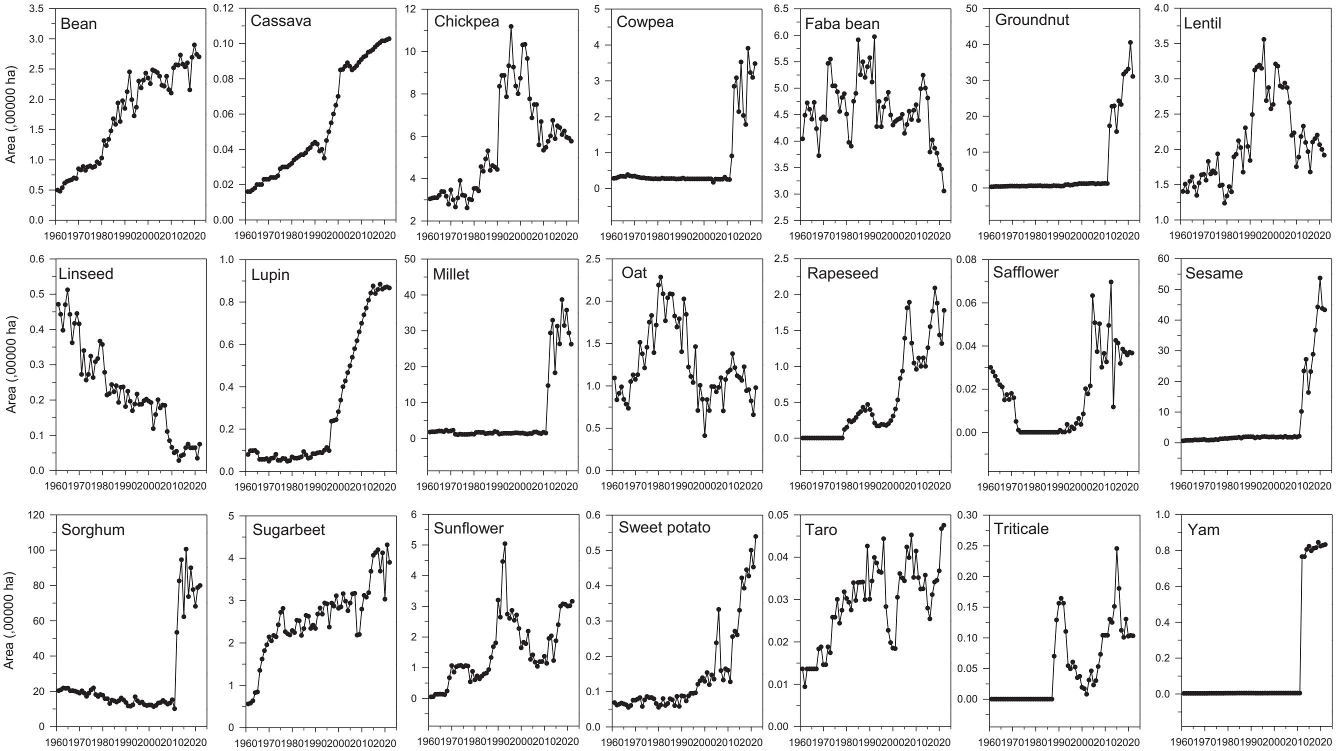

FIGURE 3 | Long-term cultivation trends of 21 neglected and underutilized (NUS) areas across 22 Middle East and North Africa (MENA) countries (1961–2022).

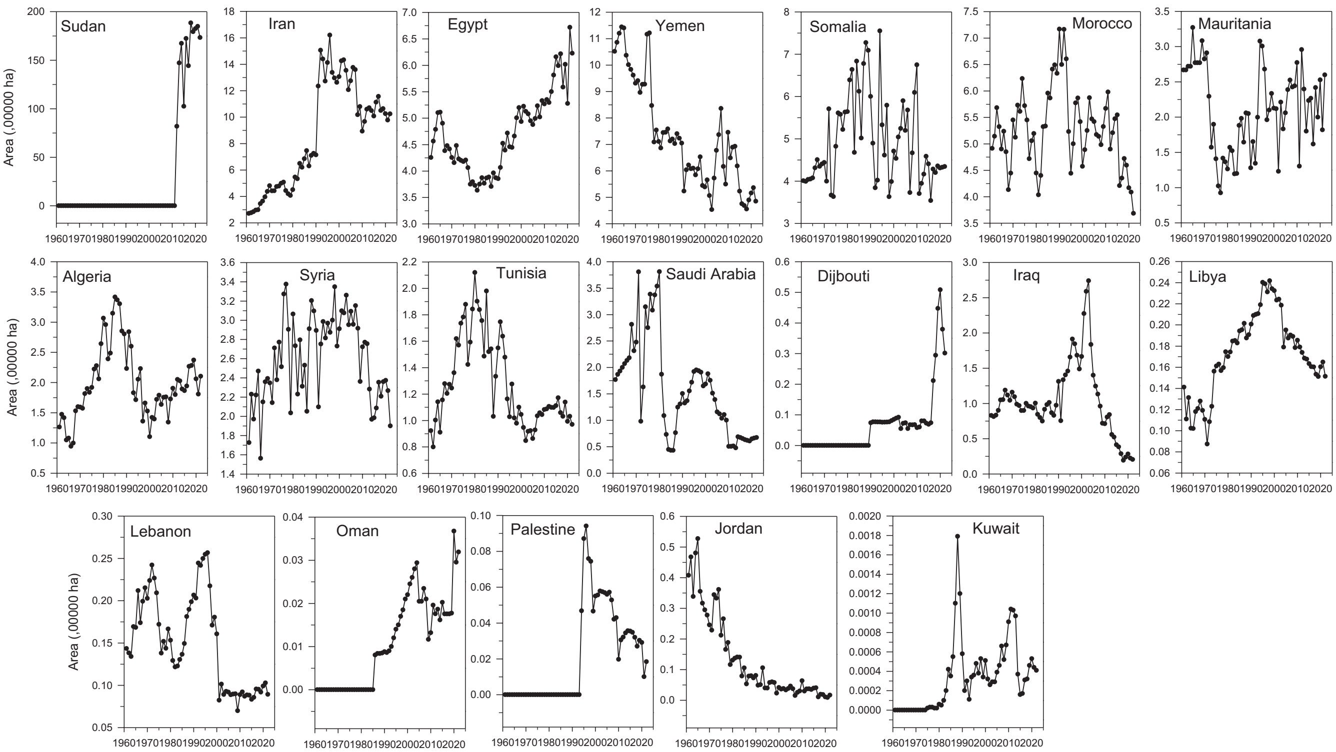

FIGURE 4 | Long-term trend of 21 (crops of Fig. 2B) neglected and underutilized (NUS) areas in 19 Middle East and North Africa (MENA) countries. Bahrain, Israel and United Arab Emirates are not included.

1996 and stabilizing around 1.0 Mha in recent years. Egypt showed moderate growth, increasing from 0.43 Mha in 1961 to 0.67 Mha in 2021. Yemen's area increased from 1.05 Mha in 1961 to 1.12 Mha in 1976, declining to 0.49 Mha in 2022. Somalia's area peaked at 0.73 Mha in 1988, with only 0.43 Mha in 2022. Morocco increased from 0.49 Mha in 1961 to 0.72 Mha in 1990, declining to 0.37 Mha in 2022 (22% decline in the last 5 years). Mauritania peaked at 0.34 Mha in 1992 but declined to 0.26 Mha in 2022. Algeria increased from 0.13 Mha in 1961 to 0.33 Mha in 1986 before declining, with 0.21 Mha recorded in 2022 (8% decline in the last 5 years). Syria increased steadily, peaking at 0.33 Mha in 1977 before declining to 0.19 Mha in 2022 (13% decline in the last 5 years). Tunisia exhibited modest growth from 0.09 Mha in 1961 to 0.21 Mha in 1976 before declining to around 0.10 Mha in 2022 (6% decline in the last 5 years). Saudi Arabia peaked at 0.38 Mha in 1971, decreasing to only 0.07 Mha in 2022. Djibouti consistently showed negligible areas under NUS. Iraq peaked at 0.27 Mha in 2003, declining to only 0.02 Mha in 2022. Libya increased steadily, peaking at 0.02 Mha in 1995 before stabilizing around 0.02 Mha in 2022 (2% decline in the last 5 years). Lebanon's area remained low, peaking at 0.03 Mha in 2007 (6% decline in the last 5 years). Oman's area remained minimal, peaking at 0.04 Mha in 2007. Palestine had negligible areas under NUS, peaking at 0.04 Mha in 2008 (33% declined in the last 5 years). Jordan peaked at 0.14 Mha in 1965, stabilizing around 0.02 Mha in recent years (a 14% decline in the last 5 years). Kuwait had negligible NUS areas.

3.1.4 | Global Trend of NUS Cultivation

Figure 5 illustrates global trends in NUS cultivation, revealing distinct regional patterns. While NUS areas have increased globally (+4%), especially in SSA (+8%), the MENA region has seen a continuous decline since 2018 (−7.0%).

3.2 | Key Challenges and Opportunities in Cultivating and Commercializing NUS in MENA Countries

3.2.1 | Trade Balance Analysis

3.2.1.1 | Import and Export Quantities. The import of NUS in the MENA region has significantly increased from 0.19 Mt. in 1961 to 8.13 Mt. in 2022 (Figure 6). Exports also grew—from 0.16 Mt. in 1961 to 3.87 Mt. in 2022—reflecting increasing demand and trade activity in NUS. In comparison, wheat imports surged from 3.52 Mt. in 1961 to 34.78 Mt. in 2022, although wheat exports have remained low, peaking at 2.11 Mt. in 1988 before decreasing to 1.34 Mt. in 2022, highlighting the region's reliance on wheat imports to meet its food requirements.

3.2.1.2 | Import and Export Values. The value of NUS imports climbed from USD 1 billion in 1961 to USD 8.98 billion in 2022. Likewise, the export value grew from USD 0.01 billion in 1961 to USD 3.35 billion in 2022.

3.2.1.3 | Trade Balance. The trade balance for NUS and wheat remains negative. NUS imports have consistently outpaced exports, resulting in a growing trade deficit in quantity

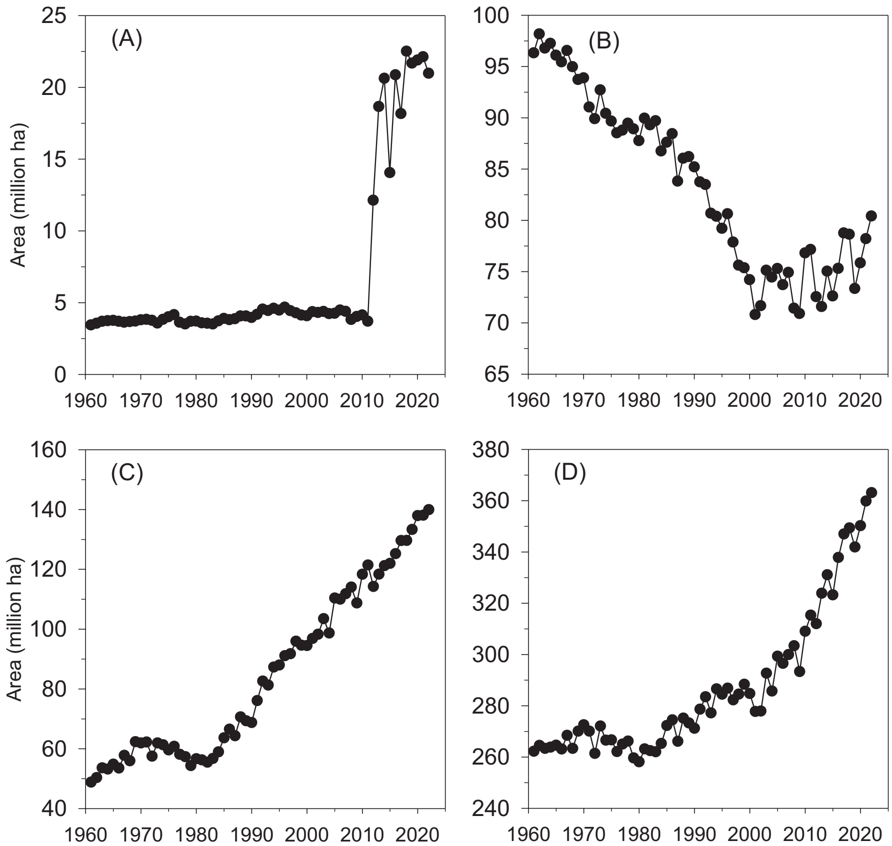

FIGURE 5 | Neglected and underutilized species (NUS) areas in the (A) Middle East and North Africa (MENA), (B) Asia, (C) sub-Saharan Africa, and (D) globally.

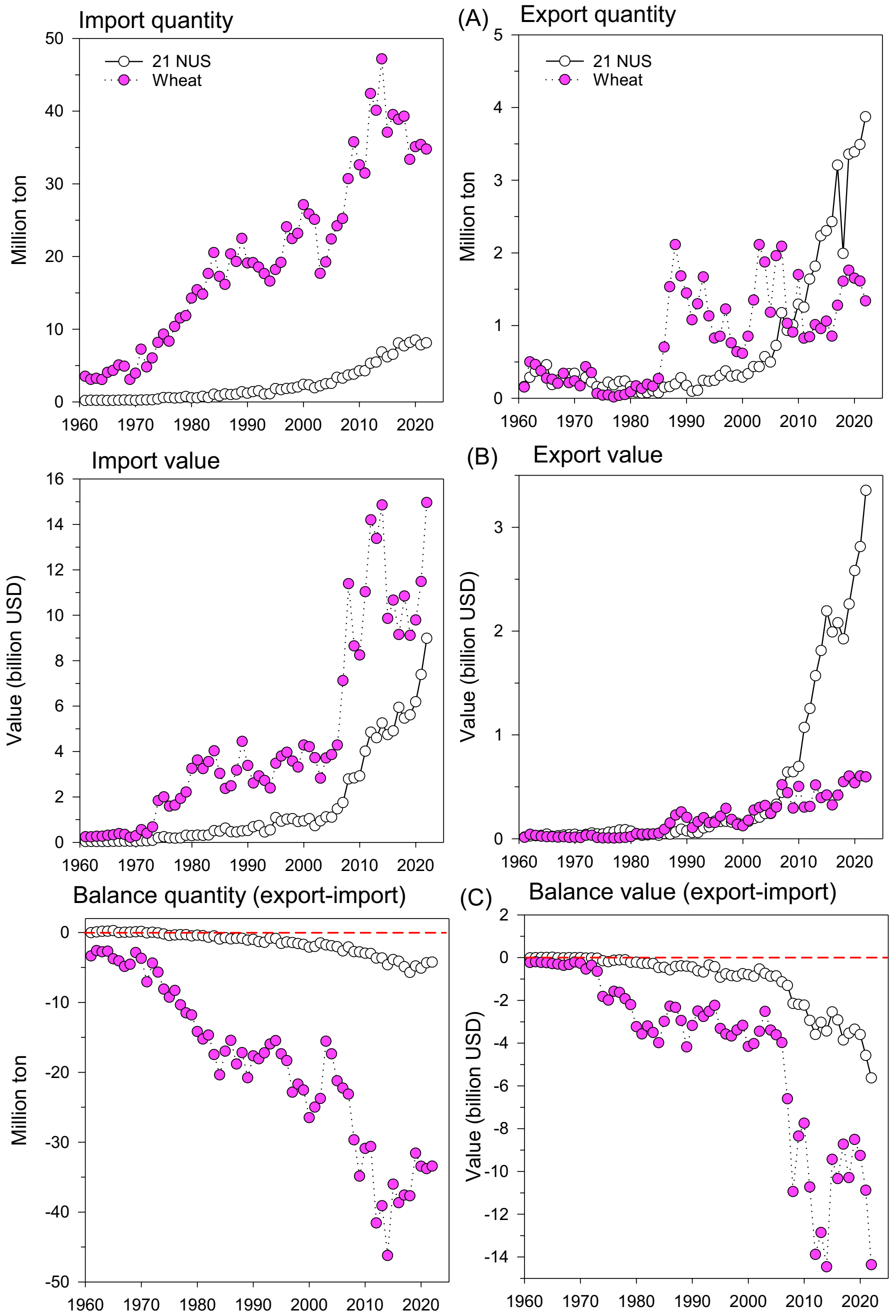

FIGURE 6 | Trade balance comparing neglected and underutilized species (NUS) with wheat in the Middle East and North Africa (MENA) region. (A) Import and export quantities, (B) import and export values, and (C) trade balance (exports minus imports). Long-term data from FAOSTAT (2024). 21 NUS are the crops shown in Fig. 2B.

and value. Wheat imports also exceeded exports significantly, contributing to a negative trade balance in quantity and value.

3.2.1.4 | **Recent (2018–2022) Trade Balance.** Between 2018 and 2022, the import quantity of NUS increased from 7.71 to 8.13 Mt., while exports grew from 1.99 to 3.87 Mt. However, the trade balance for NUS remained negative, with import revenues consistently exceeding export revenues. In contrast, wheat imports fluctuated, ultimately decreasing from 39.29 to 34.78 Mt., while exports slightly declined from 1.61 to 1.34 Mt., maintaining a negative trade balance due to high import values compared to export values.

3.3 | Nutritional and Ecological Benefits of Integrating NUS Into Local Food Systems in MENA and SSA

3.3.1 | Calorie Contribution

Figure 7 highlights the significant calorie contribution of NUS in the MENA region. Globally, NUS provide more calories than rice or wheat. When combining the calorie contributions from date (24 trillion kcal) and olive (7 trillion kcal), NUS surpass wheat as the primary calorie source. In the MENA region, wheat remains the dominant energy source, contributing 110 trillion

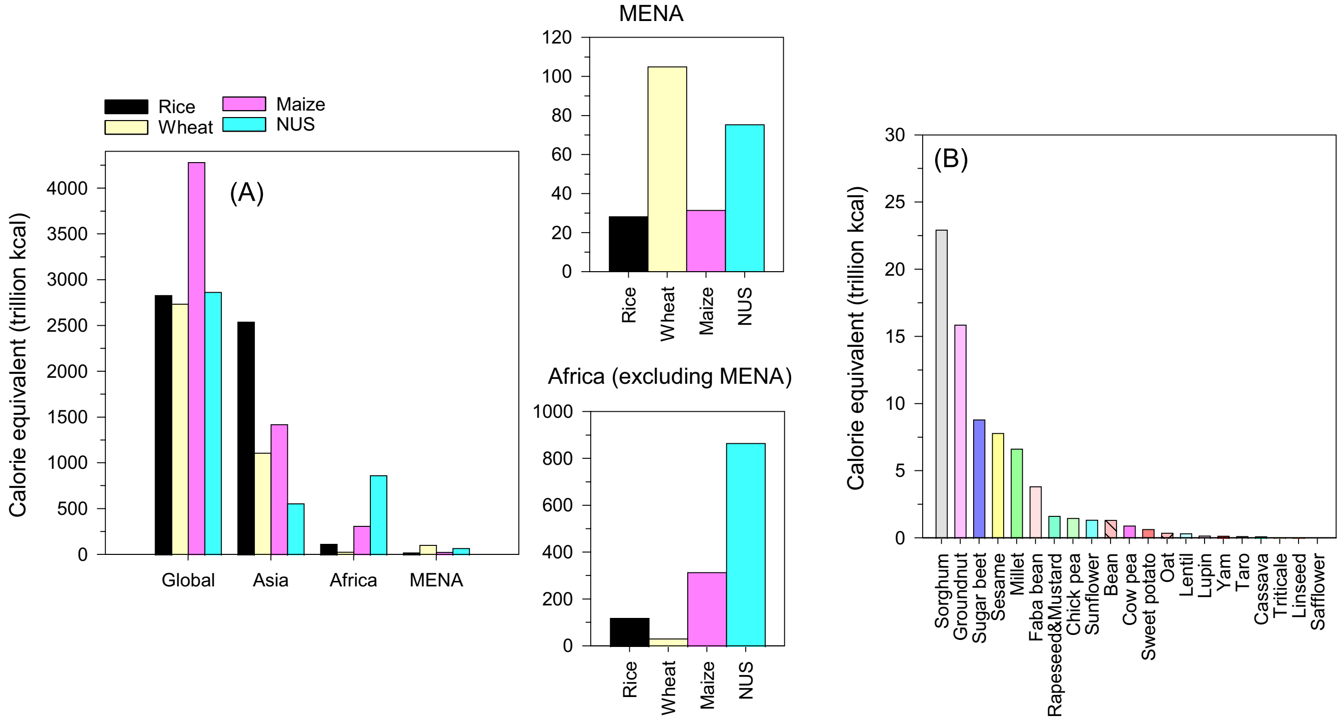

FIGURE 7 | (A) Calorie contribution from neglected and underutilized species (NUS) and major crops (rice, wheat, and maize) in the Middle East and North Africa (MENA) region and Sub-Saharan Africa, and (B) the distribution of 75.4 trillion kcal from 21 NUS (crops of Fig. 2B) in the MENA region.

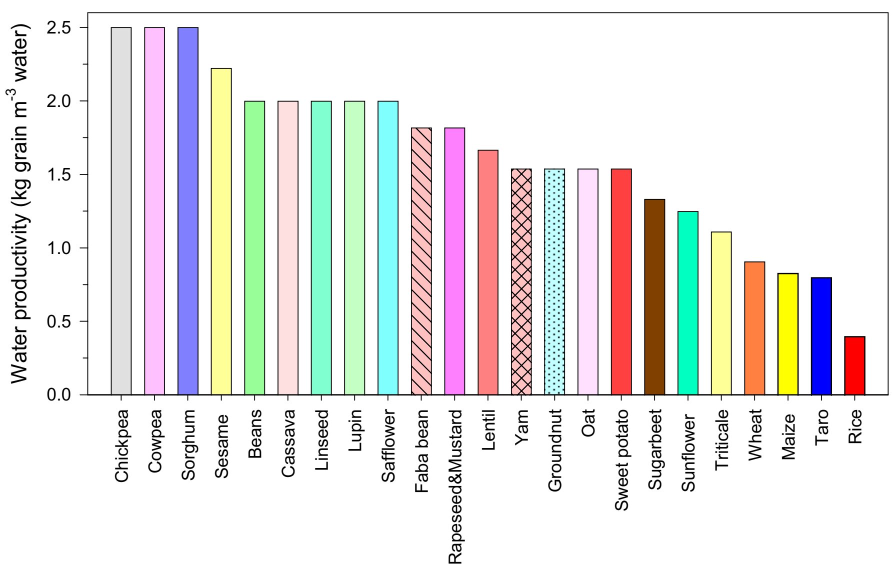

FIGURE 8 | Comparison of water productivity among neglected and underutilized species (NUS) and major crops (wheat, maize, and rice). Data from FAOSTAT (2024), Mabhaudhi et al. (2017), and other literature.

kcal, followed by NUS at 75 trillion kcal, maize at 34 trillion kcal, and rice at 28 trillion kcal. In contrast, in SSA (excluding North Africa), NUS provide 83% more nutrients than rice, wheat, and maize combined. Major calorie contributors in SSA include sorghum (22.959 trillion kcal), groundnut (15.894 trillion kcal), sugar beet (8.852 trillion kcal), sesame (7.840 trillion kcal), millet (6.675 trillion kcal), and faba bean (3.875 trillion kcal). In the MENA region, wheat and NUS provide a concentrated source of calories.

3.3.2 | Water Productivity and Heat Stress Tolerance

Figure 8 compares the water productivity and heat stress tolerance of various NUS compared with major cereals (wheat, maize, and rice) in the MENA region. NUS generally exhibit the highest water productivity, with chickpea, cowpea, and sorghum leading at approximately 2.5 kg/m^3, followed by sesame (2.22 kg/m^3) (Table 2). Other NUS, including beans, cassava, linseed, lupin, and safflower, also demonstrate strong water efficiency, with

TABLE 2 | Water productivity and tolerance to heat stress of neglected and underutilized species (NUS) and staple cereal crops.

Crop	Water productivity (kg/m^3 water)	Reference for water productivity	Maximum average temperature tolerance (°C)	Reference for heat stress tolerance
Chickpea	2.5	Devkota et al. (2022b), Oweis, Hachum, and Pala (2004)	35	Saxena (1980)
Cowpea	0.7	Belane and Dakora (2010)	38	Ehlers and Hall (1997)
Sorghum	2.5	Reddy et al. (2005)	42	Prasad, Boote, and Allen Jr (2006)
Sesame	2.22	Meena et al. (2024)	40	Kumar et al. (2022)
Beans	2	Pandey, Maranville, and Chetima (2001)	35	Terán et al. (2009)
Cassava	2	El-Sharkawy and Cock (1987)	45	El-Sharkawy and Cock (1987)
Linseed	1.8	Diederichsen and Richards (2003)	30	Diederichsen and Richards (2003)
Lupin	1.8	Dracup and Kirby (1996)	35	Dracup and Kirby (1996)
Safflower	1.7	Singh and Nimbkar (2006)	40	Singh and Nimbkar (2006)
Faba bean	1.5	Alharbi and Adhikari (2020)	25	Alharbi and Adhikari (2020)
Rapeseed & Mustard	1.5	Downey and Rimmer (1993), Devkota et al. (2018)	35	Downey and Rimmer (1993)
Lentil	1.6	Ray et al. (2023)	30	Ray et al. (2023)
Yam	1.5	Sunitha et al. (2018)	40	Sunitha et al. (2018)
Groundnut	1.5	Ravisankar et al. (2014)	35	Ravisankar et al. (2014)
Groundnut	0.5–1.1	Jain, Meena, and Bhaduri (2017)	35	Craufurd et al. (2003)
Oat	0.8–1.5	Islam et al. (2011)	30	Delatorre et al. (2021)
Sweet potato	3.5–5.0	Mabhaudhi, Chibarabada, and Modi (2018)	30	Dumbuya et al. (2021)
Sugarbeet	4.0–6.0	Saini and Brar (2018)	30	Ober and Rajabi (2010)
Sunflower	0.5–1.5	Grassini, Hall, and Mercau (2009)	34	Rondanini, Savin, and Hall (2003)
Triticale	1.0–2.0	Mrabet (2002)	32	Arseniuk (2015)
Taro	2.5–3.0	Sunitha and Sreekumar (2023)	30	Sánchez, Rasmussen, and Porter (2014)
Wheat	1.0–1.5	Mrabet (2002)	32	Porter and Gawith (1999)
Maize	1.5–2.0	Edreira et al. (2018)	35	Sánchez, Rasmussen, and Porter (2014)
Rice	0.4–1.1	Barker et al. (2004), Tuong, Bouman, and Mortimer (2005)	35	Krishnan et al. (2011)

values around 2 kg/m^3. In contrast, traditional crops like wheat (0.91 kg/m^3), maize (0.83 kg/m^3), and rice (0.4 kg/m^3) have significantly lower water productivity.

The heat stress tolerance of NUS further underscores their resilience in challenging environments. Sorghum, for instance, can tolerate temperatures up to 42°C, while cowpea and sesame can withstand up to 40°C. Crops like chickpeas, beans, lupin, safflower, and sunflower show moderate-to-high heat resilience, tolerating temperatures up to 35°C. Other NUS, including linseed, rapeseed, mustard, lentil, yam, groundnut, oat, sweet potato, sugar beet, triticale, and taro, show moderate tolerance to temperatures between 25°C and 30°C. Traditional staples like rice can tolerate up to 30°C–35°C, but its lower water productivity makes it less efficient in water-scarce conditions.

3.4 | Recommendations for Enhancing Research, Policy Support, and Market Access to Promote NUS in the MENA Region

3.4.1 | Trade-Off Among Economic and Environmental Indicators

The comparison presented in Figure 9 highlights the sustainability benefits of integrating NUS like lentil, chickpea and quinoa as relay-intercropping into the existing wheat monocropping systems in rainfed drylands. Data from field experimentation in Morocco during 2019/20 and 2020/21 growing seasons reveal that the lentil–quinoa and lentil-chickpea relay intercropping consistently outperforms wheat monocropping in sustainability indicators. Specifically, lentil–quinoa and lentil-chickpea combinations exhibit lower GHGI while enhancing

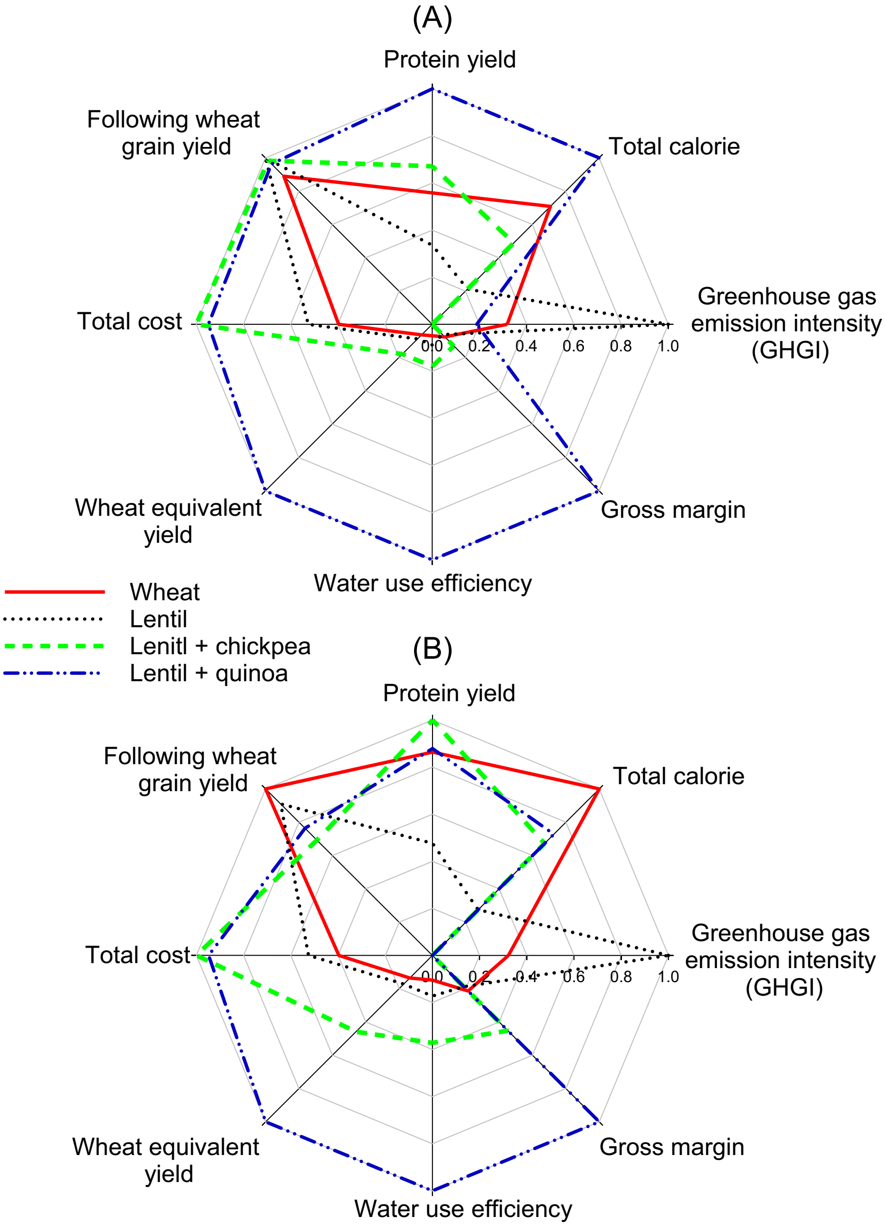

FIGURE 9 | Comparison of economic and environmental sustainability indicators for wheat, lentil, lentil + chickpea, and lentil + quinoa relay-intercropping in the (A) 2019/20 and (B) 2020/21 cropping seasons in Merchouch, Morocco.

caloric and protein yields, wheat-equivalent yield, WUE, and gross margins. This consistency across seasons underscores the robustness of incorporating NUS into traditional cereal-monocropping systems. Despite the slightly higher production costs of mixed cropping systems, their superior sustainability indicators suggest they are a promising strategy for regions like MENA, where water scarcity and climate variability are pressing concerns.

3.4.2 | Research Gaps and Required Innovations in NUS

Table 3 outlines key research gaps and innovations for enhancing NUS sustainability. Addressing these gaps will require developing resilient, nutrient-rich varieties, improving agronomic practices, and fostering market access through policy support and value chain development.

4 | Discussion

4.1 | Assessment of Current Status and Trends of NUS in the MENA Region

4.1.1 | Long-Term Trends and Global Perspective of NUS

The study reveals that NUS in the MENA region occupy more land than major cereals like wheat, maize, and rice, showcasing their adaptability and importance in arid and semi-arid environments, which is vital for food security and climate resilience (Padulosi, Thompson, and Rudebjer 2013).

Long-Term Trends of NUS Areas: From 1961 to 2022, NUS cultivation showed an overall increase, although a recent decline—from 22.52 Mha in 2018 to 21.1 Mha in 2022—raises concerns over pest infestations, climate change, and socio-economic challenges. NUS enhance resilience to climate change and water scarcity, improving water productivity with heat tolerance (Figure 8). However, declines in millet, sorghum, chickpea, faba bean, lentil, and groundnut highlight the need for pest-resistant varieties and improved agronomic practices (Padulosi, Thompson, and Rudebjer 2013; Rubiales and Fernández-Aparicio 2012).

Country-Wide Trends: Country-specific analyses showed mixed trends. While some countries show marginal increases in NUS areas, others like Yemen, Morocco, and Algeria face declines due to policy gaps, market access issues, and climatic stresses. Strategies from successful regions could offer insights for reversing these trends (Mabhaudhi et al. 2017).

Global Trends: Globally, NUS areas have declined in the MENA region since 2018, while SSA has experienced growth, indicating a need for tailored regional strategies to support NUS cultivation (Hunter et al. 2019).

4.2 | Key Challenges and Opportunities for Cultivating and Commercializing NUS

4.2.1 | Trade Balance and Economic Viability

The MENA region's growing import and export activities for NUS reflect rising demand. However, the negative trade balance indicates higher expenditure on imports than earnings from exports. This finding presents an opportunity to enhance domestic production through improved agronomic practices, market access, breeding and seed supply, and supportive policies. Diversifying production with NUS could reduce dependency on wheat imports and improve food security.

4.2.2 | Reasons for Decline in NUS Areas

Market dynamics, economic viability, and high input costs contribute to the decline in NUS areas. Farmers often prioritize staple crops with established markets and government support, leaving NUS with limited market access and profitability. Enhancing market infrastructure, value chains, and supportive policy frameworks could boost NUS viability (Mabhaudhi et al. 2017; Padulosi, Thompson, and Rudebjer 2013). Additionally, pest and disease pressures, exacerbated by climate change and soil degradation, adversely affect NUS. Developing resistant varieties and effective management strategies, especially against parasitic weeds like broomrape, is critical (Rubiales and Fernández-Aparicio 2012).

4.3 | Nutritional and Ecological Benefits of Integrating NUS Into Local Food Systems

4.3.1 | Improving Food Security and Resilience

Calorie Contribution: NUS significantly contribute to dietary energy in the MENA region, often surpassing traditional cereals in calorie provision. Crops like date and olive are crucial for nutritional security and dietary diversity (Padulosi, Thompson, and Rudebjer 2013). Excluding those crops (Date and Olive), NUS role in caloric intake in MENA region is not as substantial as that of staples like rice, wheat, and maize (Figure 7A). However, NUS excel in supplying essential micronutrients that help to address malnutrition. In much of SSA, the primary issue is not calorie deficiency but a lack of micronutrients. While this study did not focus on micro- and specialty nutrients, NUS are often promoted as nutrient-dense superfoods that enhance dietary diversity (Akram, Layla, and Ismail 2023).

Yield and Water Productivity: Many NUS, including sorghum, chickpea, and sesame, outperform traditional cereals in water productivity, making them ideal for arid and semi-arid environments. Integrating these crops can promote sustainable practices and improve resilience against climate change (Chimonyo, Modi, and Mabhaudhi 2016). The yield and water productivity of NUS vary across species and regions. For example, integrating

TABLE 3 | Research gaps and required innovations to improve production of neglected and underutilized crop species (NUS).

Crop	Research gap	Required innovations	References
Chickpea	Susceptibility to *Orobanche crenata* (broomrape) and low productivity	Develop Orobanche-resistant varieties; improve water management practices through supplemental irrigation; good agronomic practices; precision agriculture and digital tools; soil health improving solutions	Asati et al. (2022), Rubiales and Fernández-Aparicio (2012)
	Limited genetic diversity for stress tolerance and yield	Enhance genetic diversity through molecular breeding and develop high-yielding, drought-resistant varieties	Varshney et al. (2014)
Cowpea	Vulnerability to heat stress and pests such as aphids and weevils	Develop drought and heat-tolerant and pest-resistant varieties; implement integrated pest management (IPM) strategies; biofertilizers and nitrogen fixing strains	Ehlers and Hall (1997), Mabhaudhi et al. (2017)
	Limited water use efficiency in arid conditions	Improve agronomic practices focusing on water use efficiency; breed for drought tolerance	Agbicodo et al. (2009)
Sorghum	Susceptibility to drought and pests like stem borers; limited genetic diversity in local varieties	Breed drought-tolerant and pest-resistant varieties; implement advanced irrigation techniques like drip irrigation; tailored good agronmic practices; promoting intercropping with legumes; mechanized and climate smart farming practices	Hilario (2011)
	Low market value and limited processing techniques	Strengthen value chains through postharvest processing and develop sorghum-based products for diversified markets	Deribe and Kassa (2020)
Sesame	Low productivity and susceptibility to pests like *Striga hermonthica* and diseases	Develop pest-resistant varieties and IPM; improve water management practices to enhance water use efficiency; good agronomic water-efficient and climate-smart practices; mechanization and post-harvest techniques	Teklu et al. (2021)
	Poor adaptation to various ecological zones and limited genetic diversity	Enhance genetic diversity through molecular markers and develop stress-tolerant varieties adapted to different ecological zones	Teklu et al. (2021)
Beans	Lack of climate-resilient varieties and susceptibility to pests and diseases like rust and Fusarium wilt	Develop climate-resilient and disease-resistant varieties; adopt IPM strategies	Ehlers and Hall (1997), Mabhaudhi et al. (2017)
	Poor agronomic practices and limited market access	Strengthen value chains through postharvest processing and branding; tailored agronomic practices to local conditions	Agbicodo et al. (2009)
Cassava	Susceptibility to pests and diseases such as cassava mosaic disease and brown streak disease	Develop disease-resistant and high-yielding varieties through genetic improvement; improve soil management practices to enhance productivity	Bellotti, Herrera Campo, and Hyman (2012)
	Poor soil fertility and limited research on sustainable soil management practices	Promote organic fertilizers and sustainable soil management practices to improve soil fertility and crop yields	Bellotti, Herrera Campo, and Hyman (2012)

(Continues)

TABLE 3 | (Continued)

Crop	Research gap	Required innovations	References
Linseed	Vulnerability to drought stress and poor adaptation to varying climatic conditions	Develop drought-tolerant varieties and improve agronomic practices to enhance resilience and yield	Biradar et al. (2016)
	Susceptibility to diseases such as powdery mildew and fusarium wilt	Breed for disease-resistant varieties and implement integrated disease management strategies	Biradar et al. (2016)
Lupin	Low yield potential and susceptibility to anthracnose disease	Develop high-yielding, disease-resistant varieties through breeding programs; improve agronomic practices for enhanced productivity	Sweetingham and Kingwell (2008)
	Limited market access and value chain development	Strengthen value chains through postharvest processing and promote lupin-based products in niche markets	Sweetingham and Kingwell (2008)
Safflower	Low yield and susceptibility to drought and diseases such as Alternaria leaf blight	Breed for drought-tolerant, disease-resistant varieties; develop improved agronomic practices tailored to local conditions	Emongor et al. (2017)
	Limited research on oil extraction and processing techniques	Develop advanced oil extraction and processing techniques to increase profitability and marketability	Emongor et al. (2017)
Faba bean	Susceptibility to diseases, such as Ascochyta blight and chocolate spot, and parasitic weeds like *Orobanche* spp.	Develop disease-resistant and Orobanche-resistant varieties; improve agronomic practices such as crop rotation and use of biofertilizers	Duc et al. (2015), Hauggaard-Nielsen, Peoples, and Jensen (2011)
	Weak market linkages and postharvest losses	Strengthen value chains through postharvest processing and market development to reduce losses and improve profitability	Duc et al. (2015), Hauggaard-Nielsen, Peoples, and Jensen (2011)
Rapeseed and mustard	Susceptibility to pests such as aphids and diseases like blackleg	Develop pest-resistant and drought-tolerant varieties; implement IPM and improve agronomic practices	Devkota et al. (2018), Shahidi (1990)
	Poor adaptation to drought conditions	Optimize fertilization and irrigation practices; develop climate-resilient varieties adapted to dryland conditions	Devkota et al. (2018), Shahidi (1990)
Lentil	Susceptibility to diseases such as rust and Fusarium wilt, and drought stress	Develop disease-resistant and drought-tolerant varieties; improve soil fertility management and optimal planting times	Nehra et al. (2021), Yadav et al. (2007)
	Limited market access and value chain development	Strengthen market linkages and enhance value chains through postharvest processing and branding	Nehra et al. (2021), Yadav et al. (2007)
Yam	Susceptibility to pests like yam beetles and diseases such as yam mosaic virus	Develop pest-resistant and disease-tolerant yam varieties through genetic improvement; implement IPM strategies	Amusa et al. (2003), Korada, Naskar, and Edison (2010)
	Poor storage and postharvest processing techniques	Improve storage facilities and postharvest processing techniques to reduce losses and increase marketability	Amusa et al. (2003), Korada, Naskar, and Edison (2010)

(Continues)

TABLE 3 | (Continued)

Crop	Research gap	Required innovations	References
Groundnut	Susceptibility to aflatoxin contamination, pests, and diseases like groundnut rosette virus	Develop drought-tolerant, pest-resistant varieties; implement IPM and postharvest management practices to reduce aflatoxin	Ajeigbe et al. (2015), Okello et al. (2010)
	Low soil fertility and high input costs	Improve soil fertility through organic and inorganic fertilizers; reduce input costs through subsidies and financial support for smallholder farmers	Ajeigbe et al. (2015), Okello et al. (2010)
Oat	Susceptibility to crown rust and other fungal diseases; poor adaptation to climate variability	Breed for disease-resistant and climate-resilient varieties; implement improved agronomic practices tailored to diverse climatic conditions	Bilgrami and Choudhary (1998), Dwivedi et al. (2003)
	Limited research on nutritional enhancement and value-added products	Develop nutritionally enhanced oat varieties and innovative oat-based products to increase market demand and value addition	Bilgrami and Choudhary (1998), Dwivedi et al. (2003)
Sweet potato	Susceptibility to pests like sweet potato weevil and diseases such as sweet potato virus disease (SPVD)	Develop pest-resistant and disease-tolerant varieties through breeding; implement IPM strategies	Low et al. (2009), Ngailo et al. (2013)
	Poor postharvest management and storage techniques resulting in high losses	Improve postharvest processing and storage facilities to reduce losses and increase shelf life and marketability	Low et al. (2009), Ngailo et al. (2013)
Sugarbeet	Susceptibility to pests such as sugarbeet root maggot and diseases like Rhizoctonia root rot	Develop pest-resistant and disease-resistant varieties; implement IPM and improve crop rotation practices	Panella et al. (2014), Stevanato et al. (2019)
	High water requirement and poor water use efficiency in arid regions	Breed drought-tolerant varieties; implement water-saving irrigation technologies to improve water use efficiency	Panella et al. (2014), Stevanato et al. (2019)
Sunflower	Susceptibility to pests like sunflower moth and diseases such as downy mildew	Develop pest- and disease-resistant varieties through breeding; IPM strategies	Kaya, Jocic, and Miladinovic (2012), Sala et al. (2012)
	Poor adaptation to drought conditions and limited research on enhancing oil content and quality	Breed for drought-resistant varieties with improved oil content and quality; develop advanced oil extraction and processing techniques	Kaya, Jocic, and Miladinovic (2012), Sala et al. (2012)
Triticale	Limited genetic diversity leading to poor adaptability in diverse environmental conditions	Breed for enhanced genetic diversity and develop stress-tolerant varieties through hybridization and advanced breeding techniques	Mergoum et al. (2019)
	Low market demand and limited research on value-added products	Promote triticale-based products in niche markets; strengthen value chains through postharvest processing and branding	Mergoum et al. (2019)
Taro	Susceptibility to diseases like taro leaf blight and pests like taro beetle; high water requirements	Develop disease-resistant, drought-tolerant varieties; implement efficient irrigation systems and IPM strategies	Deo et al. (2009), Ravi et al. (2021)
	Poor postharvest processing techniques, resulting in high losses and reduced marketability	Improve postharvest processing and storage techniques to increase shelf life and reduce losses	Deo et al. (2009), Ravi et al. (2021)

(Continues)

TABLE 3 | (Continued)

Crop	Research gap	Required innovations	References
Quinoa	Limited research on suitable agronomic practices for diverse MENA environments; susceptibility to quinoa downy mildew	Develop high-yielding, nutrient-rich varieties; research optimized agronomic practices for different environments; breed for disease resistance	Choukr-Allah et al. (2016), Taaime et al. (2023)
	Weak market access and value chain development for quinoa in the MENA region	Strengthen market linkages through value chain development; promote quinoa as a superfood to increase demand and profitability	Choukr-Allah et al. (2016), Taaime et al. (2023)
Millet	Limited genetic diversity and susceptibility to drought and pests	Breed for enhanced genetic diversity and develop drought- and pest-resistant varieties; research improved agronomic practices	Das and Rakshit (2016), Goron and Raizada (2015), Mabhaudhi et al. (2017)
	Poor market access and limited research on the nutritional benefits of millet	Strengthen value chains through postharvest processing and branding; promote millet as a nutrient-dense food in local and international markets	Chivenge et al. (2015), Das and Rakshit (2016), Goron and Raizada (2015), Mabhaudhi et al. (2017), Mustafa, Mabhaudhi, and Massawe (2021)

chickpeas and lentils into existing cropping systems significantly improved WUE compared to traditional monocultures. NUS must align with existing systems to maximize these benefits (Yang et al. 2024).

Heat Tolerance: NUS like sorghum, chickpea, and sesame also exhibit heat stress tolerance, making them well suited for cultivation in the MENA region. Promoting these crops could support sustainable agricultural practices in water-scarce and heat-stressed environments (Rosero et al. 2020).

Economic Viability: Despite their potential, NUS face high input costs and limited market access. Reducing input costs through subsidies and improving market linkages could enhance market viability (Kusse, Ermias, and Darcho 2022).

Trade-Offs Among Sustainability Indicators: Integrating NUS like lentils, chickpea and quinoa into farming systems can enhance sustainability and resilience by lowering GHGI, increasing calorie and protein yields, and improving WUE compared to traditional cereals. Successful integration requires consideration of local conditions, market dynamics, and farmer preferences (Bazile, Bertero, and Nieto 2015).

These findings underscore the importance of NUS in advancing the goals outlined in the COP28 Declaration on Sustainable Agriculture and Resilient Food Systems. By positioning NUS within the value chains for agrifood systems framework, their potential for transforming dryland agriculture can be realized, supporting sustainable climate action in the MENA region.

4.4 | Recommendations for Enhancing Research, Policy Support, and Market Access

4.4.1 | Potential of NUS

Market Dynamics and Economic Viability: The lack of market access and economic incentives often compels farmers to prioritize staple crops with established markets and government support. Addressing this issue through robust market infrastructure, enhanced value chains, and supportive policies is crucial (Mabhaudhi et al. 2017; Padulosi, Thompson, and Rudebjer 2013). Economic policies and subsidies typically favor staple crops, further marginalizing NUS (Ebert 2014).

High Input Costs: High input costs for seeds, fertilizers, and pesticides make NUS less economically viable. For instance, cowpea and sorghum cultivation in Sudan faces challenges due to the high cost of quality seeds and a lack of financial incentives (Mabhaudhi et al. 2017). Targeted subsidies and financial support are necessary to improve competitiveness.

Pest and Disease Pressure: NUS in the MENA region, particularly those affected by broomrape (*Orobanche* spp.), face substantial yield losses. Broomrape, a parasitic weed, attaches to host plant roots, siphoning nutrients and leading to severe yield losses (Rubiales and Fernández-Aparicio 2012). Developing resistant varieties and effective management strategies is essential.

Climate Change and Variability: Climate change and variability exacerbate the challenges also for NUS, particularly in marginal areas. For example, the declining productivity of crops like millet and sorghum in North Africa is attributed to the increasing difficulty of maintaining yields under changing climatic conditions (El-Beltagy, Erskine, and Ryan 2004; Leal Filho 2010). Limited genetic improvement and breeding efforts for NUS make them less resilient to environmental stresses than major crops like wheat and maize (FAO 2010). R&D efforts must focus on enhancing resilience to climatic challenges.

Soil Degradation: Soil degradation from overuse, erosion, and salinization impacts NUS productivity by reducing the availability of essential nutrients and organic matter (Lal 2001). For example, poor soil conditions limit groundnut and taro growth and productivity, leading farmers to abandon these crops in favor of more resilient or profitable alternatives. Addressing soil health and fertility issues is crucial for sustainable cultivation.

Low or No Research and Development (R&D) Funding: NUS receive significantly less R&D funding than staple crops. For example, the CGIAR system prioritizes major staple crops, driving advancements in their productivity and resilience (Pingali 2012). Increased investment in R&D is needed to enhance breeding, agronomic practices, and technology dissemination of NUS (FAO; IFAD; UNICEF; WFP; WHO 2017).

4.4.2 | Research Implications and Limitations

Improving agronomic practices, advancing breeding and genetic improvements, developing robust market infrastructure, and enhancing postharvest processing techniques are vital to unlocking the potential of NUS in the MENA region. Strengthening extension services to support NUS cultivation, investing in R&D, and creating supportive policies are key to advancing NUS (Chimonyo, Modi, and Mabhaudhi 2016; Padulosi, Thompson, and Rudebjer 2013). International organizations such as the FAO and ICARDA (International Center for Agricultural Research in the Dry Areas) are pivotal in promoting NUS through research, advocacy, and capacity-building initiatives (El-Beltagy, Erskine, and Ryan 2004; FAO 2010). Moreover, addressing the region's reliance on wheat imports highlights the need to boost local NUS production, reduce import dependency, and improve trade balance.

4.4.3 | Way Forward

In February, 2024, ICARDA, Agricultural Model Intercomparison and Improvement Project (AgMIP), and Mohammed IV Polytechnic University (UM6P) organized a 2-day hybrid conference in Rabat, Morocco, on innovations for sustainable NUS production in the MENA region (https://www.icarda.org/media/news/conference-innovations-sustainable-production-neglected-and-underutilized-crop-species). With over 1000 participants (in-person and online) from 28 countries, the conference explored 41 NUS that can feed 278 million people. It generated 27 key recommendations (https://www.icarda.org/sites/default/files/2024-02/nus-recommendations.pdf) to enhance research, development, and policy understanding of NUS across MENA, West Asia, East Asia, and SSA (Supporting Information). In February 2024, a 2-day workshop in Benguerir, Morocco, titled "Addressing Water Scarcity in Agriculture and the Environment" (AWSAMe)—organized by the Land and Water Division of FAO and Centre for International Cooperation in Agricultural Research for Development (CIRAD)—brought together invited scientists from South Sudan, Malawi, Morocco, and Cabo Vert, who provided similar recommendations.

Similarly, by supporting research, development, and market access, VACS (The Vision for Adapted Crops and Soils) can offer critical pathways for improving NUS in dryland regions. With increased funding and investment, especially in MENA, Central and West Asia, and SSA, VACS can strengthen agrifood value chains, promote sustainable production, and enhance resilience in vulnerable farming communities. Mobilizing financial support for research and innovation in these regions is crucial to ensuring NUS thrive in drylands and supporting climate adaptation and food security goals.

5 | Conclusions

NUS offer significant potential to address food and nutrition security and agricultural sustainability challenges in MENA and SSA. To fully harness these benefits, targeted agronomic practices, investment in crop improvements, development of robust market infrastructures and seed supply systems, and enhanced postharvest processing are essential. Policy support and increased research funding are needed to overcome barriers to NUS adoption and unlock their full potential. Integrating NUS into mainstream agriculture can diversify food sources, improve farming system resilience, and promote sustainable, inclusive agricultural practices. By aligning with the COP28 Declaration and Global Strategy for Resilient Drylands (GSRD) of CGIAR (https://www.icarda.org/media/news/road-global-strategy-resilient-drylands#:~:text=The%20Global%20Strategy%20for%20Resilient,enhancing%20soil%20and%20water%20management), this study highlights the transformative potential of NUS in advancing sustainable agriculture, food security, and resilience in MENA and SSA. Their inclusion in agrifood systems can support climate action and contribute to achieving sustainable development goals, particularly in dryland areas. Focusing on these areas will enable MENA and SSA countries to make significant progress in building resilient agricultural systems that support food security and economic development. Continued research, investment in breeding programs, and the establishment of strong market linkages are critical to maximizing the benefits of NUS in the MENA and SSA regions.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

Agbicodo, E. M., C. A. Fatokun, S. Muranaka, R. G. F. Visser, and C. G. Linden Van Der. 2009. "Breeding Drought Tolerant Cowpea: Constraints, Accomplishments, and Future Prospects." *Euphytica* 167: 353–370. https://doi.org/10.1007/s10681-009-9893-8.

Agoud, S., and J. Mabrouki. 2024. "Carbon and Water Efficiency Study on Growing Neglected and Underutilized Crops and Its Environmental Benefits in the MENA Region." In *Advancements in Climate and Smart Environment Technology*, 1–8. Hershey, Pennsylvania, USA: IGI Global. https://doi.org/10.4018/979-8-3693-3807-0.ch001.

Ajeigbe, H. A., F. Waliyar, C. A. Echekwu, et al. 2015. "A Farmer's Guide to Profitable Groundnut Production in Nigeria." http://oar.icrisat.org/id/eprint/8856.

Akram, I., A. Layla, and T. Ismail. 2023. "Exploring Neglected and Underutilized Plant Foods to Fight Malnutrition and Hunger in South Asia." In *Neglected Plant Foods of South Asia: Exploring and Valorizing Nature to Feed Hunger*, 51–71. Cham, Switzerland: Springer. https://doi.org/10.1007/978-3-031-37077-9_3.

Alharbi, N. H., and K. N. Adhikari. 2020. "Factors of Yield Determination in Faba Bean (*Vicia faba*)." *Crop and Pasture Science* 71, no. 4: 305–321. https://doi.org/10.1071/CP19103.

Amusa, N. A., A. A. Adigbite, S. Muhammed, and R. A. Baiyewu. 2003. "Yam Diseases and Its Management in Nigeria." *African Journal of Biotechnology* 2, no. 12: 497–502. https://doi.org/10.5897/AJB2003.000-1099.

Arseniuk, E. 2015. "Triticale Abiotic Stresses—An Overview." *Triticale*: 69–81. https://doi.org/10.1007/978-3-319-22551-7_4.

Asati, R., M. K. Tripathi, S. Tiwari, R. K. Yadav, and N. Tripathi. 2022. "Molecular Breeding and Drought Tolerance in Chickpea." *Life* 12, no. 11: 1846. https://doi.org/10.3390/life12111846.

Barker, R., T. P. Tuong, Y. Li, E. G. Castillo, and B. A. M. Bouman. 2004. "Growing More Rice With Less Water: Research Findings From a Study in China." *Paddy and Water Environment* 2, no. 4: 185. https://doi.org/10.1007/s10333-004-0067-y.

Bazile, D., H. D. Bertero, and C. Nieto. 2015. *State of the Art Report on Quinoa Around the World in 2013*. Rome, Italy: FAO.

Belane, A. K., and F. D. Dakora. 2010. "Symbiotic N 2 Fixation in 30 Field-Grown Cowpea (*Vigna unguiculata* L. Walp.) Genotypes in the Upper West Region of Ghana Measured Using 15 N Natural Abundance." *Biology and Fertility of Soils* 46: 191–198. https://doi.org/10.1007/s00374-009-0415-6.

Bellotti, A., B. V. Herrera Campo, and G. Hyman. 2012. "Cassava Production and Pest Management: Present and Potential Threats in a Changing Environment." *Tropical Plant Biology* 5: 39–72. https://doi.org/10.1007/s12042-011-9091-4.

Bilgrami, K. S., and A. K. Choudhary. 1998. "Mycotoxins in Preharvest Contamination of Agricultural Crops." In *Mycotoxins in Agriculture and Food Safety*, 19–62. Boca Raton, Florida, USA: CRC Press.

Biradar, S. A., K. Ajithkumar, B. Rajanna, et al. 2016. "Prospects and Challenges in Linseed (*Linum usitatissimum* L.) Production: A Review." *Journal of Oilseeds Research* 33, no. 1: 1–13.

Brouwer, C., and M. Heibloem. 1986. *Irrigation Water Management Training Manual No. 3: Irrigation Water Management: Irrigation Water Needs*. Rome: FAO, International Support Programme for Irrigation Water Management, Land and Water Development Division.

Chimonyo, V. G. P., A. T. Modi, and T. Mabhaudhi. 2016. "Simulating Yield and Water Use of a Sorghum–Cowpea Intercrop Using APSIM." *Agricultural Water Management* 177: 317–328. https://doi.org/10.1016/j.agwat.2016.08.021.

Chivenge, P., T. Mabhaudhi, A. T. Modi, and P. Mafongoya. 2015. "The Potential Role of Neglected and Underutilised Crop Species as Future Crops Under Water Scarce Conditions in Sub-Saharan Africa." *International Journal of Environmental Research and Public Health* 12, no. 6: 5685–5711. https://doi.org/10.3390/ijerph120605685.

Choukr-Allah, R., N. K. Rao, A. Hirich, et al. 2016. "Quinoa for Marginal Environments: Toward Future Food and Nutritional Security in MENA and Central Asia Regions." *Frontiers in Plant Science* 7: 346. https://doi.org/10.3389/fpls.2016.00346.

Craufurd, P. Q., P. V. V. Prasad, V. G. Kakani, T. R. Wheeler, and S. N. Nigam. 2003. "Heat Tolerance in Groundnut." *Field Crops Research* 80, no. 1: 63–77. https://doi.org/10.1016/S0378-4290(02)00155-7.

Das, I. K., and S. Rakshit. 2016. "Millets, Their Importance, and Production Constraints." In *Biotic Stress Resistance in Millets*, 3–19. Amsterdam, Netherlands: Elsevier. https://doi.org/10.1016/B978-0-12-804549-7.00001-9.

Dawson, I. K., S. E. Park, S. J. Attwood, et al. 2019. "Contributions of Biodiversity to the Sustainable Intensification of Food Production." *Global Food Security* 21: 23–37. https://doi.org/10.1016/j.gfs.2019.07.002.

Delatorre, C. A., V. de Freitas Duarte, A. Wairich, G. P. Fraga, M. P. Ribeiro, and H. E. Lazzari. 2021. "Oat Development in Response to Temperature." *Ciência Rural* 52, no. 1: e20210198. https://doi.org/10.1590/0103-8478cr20210198.

Deo, P. C., A. P. Tyagi, M. Taylor, D. K. Becker, and R. M. Harding. 2009. "Improving Taro (*Colocasia esculenta* var. *esculenta*) Production Using Biotechnological Approaches." *South Pacific Journal of Natural and Applied Sciences* 27, no. 1: 6–13. https://doi.org/10.1071/SP09002.

Deribe, Y., and E. Kassa. 2020. "Value Creation and Sorghum-Based Products: What Synergetic Actions Are Needed?" *Cogent Food & Agriculture* 6, no. 1: 1722352. https://doi.org/10.1080/23311932.2020.1722352.

Devkota, K. P., S. E. J. Beebout, S. Yadav, and M. A. Bunquin. 2022a. "Setting Sustainability Targets for Irrigated Rice Production and Application of the Sustainable Rice Platform Performance Indicators." *Environmental Impact Assessment Review* 92: 106697. https://doi.org/10.1016/j.eiar.2021.106697.

Devkota, K. P., M. Devkota, L. Khadka, et al. 2018. "Nutrient Responses of Wheat and Rapeseed Under Different Crop Establishment and Fertilization Methods in Contrasting Agro-Ecological Conditions in Nepal." *Soil and Tillage Research* 181: 46–62. https://doi.org/10.1016/j.still.2018.04.001.

Devkota, K. P., M. Devkota, G. P. Paudel, and A. J. McDonald. 2021. "Coupling Landscape-Scale Diagnostics Surveys, On-Farm Experiments, and Simulation to Identify Entry Points for Sustainably

Closing Rice Yield Gaps in Nepal." *Agricultural Systems* 192: 103182. https://doi.org/10.1016/j.agsy.2021.103182.

Devkota, M., Y. Singh, Y. A. Yigezu, I. Bashour, R. Mussadek, and R. Mrabet. 2022b. "Conservation Agriculture in the Drylands of the Middle East and North Africa (MENA) Region: Past Trend, Current Opportunities, Challenges and Future Outlook." *Advances in Agronomy* 172: 253–305. https://doi.org/10.1016/bs.agron.2021.11.001.

Devkota, M., and V. Nangia. 2022. *Diversified Cropping System: Relay Intercropping of Lentils with Chickpeas (Morocco)*. WOCAT SLM technology. https://mel.cgiar.org/reporting/download/hash/1424a7bce78f0fbcbe081f08a7ee7b37.

Diederichsen, A., and K. Richards. 2003. "Cultivated Flax and the Genus *Linum* L.: Taxonomy and Germplasm Conservation." In *Flax*, 34–66. Boca Raton, Florida, USA: CRC Press.

Downey, R. K., and S. R. Rimmer. 1993. "Agronomic Improvement in Oil Seed." *Brassicas Advances in Agronomy* 50: 1–66.

Dracup, M., and E. J. M. Kirby. 1996. "Pod and Seed Growth and Development of Narrow-Leafed Lupin in a Water Limited Mediterranean-Type Environment." *Field Crops Research* 48, no. 2–3: 209–222. https://doi.org/10.1016/S0378-4290(96)00040-8.

Duc, G., J. M. Aleksić, P. Marget, et al. 2015. "Faba bean." *Grain Legumes*: 141–178. https://doi.org/10.1007/978-1-4939-2797-5_5.

Dumbuya, G., H. A. Alemayehu, M. M. Hasan, M. Matsunami, and H. Shimono. 2021. "Effect of Soil Temperature on Growth and Yield of Sweet Potato (*Ipomoea batatas* L.) Under Cool Climate." *Journal of Agricultural Meteorology* 77, no. 2: 118–127. https://doi.org/10.2480/agrmet.D-20-00043.

Dwivedi, S. L., J. H. Crouch, S. N. Nigam, M. E. Ferguson, and A. H. Paterson. 2003. "Molecular Breeding of Groundnut for Enhanced Productivity and Food Security in the Semi-Arid Tropics: Opportunities and Challenges." *Advances in Agronomy* 80: 153–221. https://doi.org/10.1016/S0065-2113(03)80004-4.

Ebert, A. W. 2014. "Potential of Underutilized Traditional Vegetables and Legume Crops to Contribute to Food and Nutritional Security, Income and More Sustainable Production Systems." *Sustainability* 6, no. 1: 319–335. https://doi.org/10.3390/su6010319.

Edreira, J. I. R., N. Guilpart, V. Sadras, et al. 2018. "Water Productivity of Rainfed Maize and Wheat: A Local to Global Perspective." *Agricultural and Forest Meteorology* 259: 364–373. https://doi.org/10.1016/j.agrformet.2018.05.019.

Ehlers, J. D., and A. E. Hall. 1997. "Cowpea (*Vigna unguiculata* L. walp.)." *Field Crops Research* 53, no. 1–3: 187–204. https://doi.org/10.1016/S0378-4290(97)00031-2.

El-Beltagy, A., W. Erskine, and J. Ryan. 2004. "Dryland Research at ICARDA: Achievements and Future Directions." *Challenges and Strategies of Dryland Agriculture* 32: 417–434. https://doi.org/10.2135/cssaspecpub32.c25.

El-Sharkawy, M. A., and J. H. Cock. 1987. "Response of Cassava to Water Stress." *Plant and Soil* 100: 345–360. https://doi.org/10.1007/BF02370950.

Emongor, V., O. Oagile, D. Phuduhudu, and P. Oarabile. 2017. *Safflower Production*. Gaborone: Botswana University of Agriculture and Natural Resources.

FAO. 2010. *The Second Report on the State of the World's Plant Genetic Resources for Food and Agriculture*. Vol. 2. Rome, Italy: Food & Agriculture Organization of the UN (FAO).

FAO; IFAD; UNICEF; WFP; WHO. 2017. *The State of Food Security and Nutrition in the World 2017. Building Resilience for Peace and Food Security*. Rome: FAO. https://openknowledge.fao.org/handle/20.500.14283/I7695EN; http://www.fao.org/3/i7695en/i7695en.pdf.

FAOSTAT. 2024. "United Nations Food and Agricultural Organisation." http://www.fao.org/faostat/en/#data.

Gaur, M. K., and V. R. Squires. 2018. "Geographic Extent and Characteristics of the World's Arid Zones and Their Peoples." In *Climate Variability Impacts on Land Use and Livelihoods in Drylands*, edited by M. K. Gaur and V. R. Squires, 3–20. Cham, Switzerland: Springer International Publishing. https://doi.org/10.1007/978-3-319-56681-8_1.

Goron, T. L., and M. N. Raizada. 2015. "Genetic Diversity and Genomic Resources Available for the Small Millet Crops to Accelerate a New Green Revolution." *Frontiers in Plant Science* 6: 157. https://doi.org/10.3389/fpls.2015.00157.

Grassini, P., A. J. Hall, and J. L. Mercau. 2009. "Benchmarking Sunflower Water Productivity in Semiarid Environments." *Field Crops Research* 110, no. 3: 251–262. https://doi.org/10.1016/j.fcr.2008.09.006.

Hadebe, S. T., A. T. Modi, and T. Mabhaudhi. 2017. "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* 203, no. 3: 177–191. https://doi.org/10.1111/jac.12191.

Hauggaard-Nielsen, H., M. B. Peoples, and E. S. Jensen. 2011. "Faba Bean in Cropping Systems." *Grain Legumes* 56: 32–33. https://backend.orbit.dtu.dk/ws/portalfiles/portal/5678198/Grain%20Legumes%2056.pdf.

Hilario, F. A. 2011. *ICRISAT Innovations Shape the Future of Drylands*. Patancheru, Telangana, India: International Crop Research Institute for Semi Arid Tropics. https://oar.icrisat.org/1933/1/ICRISAT_innovations_shape_the_future_of_drylands.pdf.

Hunter, D., T. Borelli, D. M. O. Beltrame, et al. 2019. "The Potential of Neglected and Underutilized Species for Improving Diets and Nutrition." *Planta* 250: 709–729. https://doi.org/10.1007/s00425-019-03169-4.

Islam, M. R., A. E. Eneji, C. Ren, J. Li, and Y. Hu. 2011. "Impact of Water-Saving Superabsorbent Polymer on Oat (*Avena* spp.) Yield and Quality in an Arid Sandy Soil." *Scientific Research and Essays* 6, no. 4: 720–728. https://academicjournals.org/article/article1380714700_Islam%20et%20al.pdf.

Jain, N. K., H. N. Meena, and D. Bhaduri. 2017. "Improvement in Productivity, Water-Use Efficiency, and Soil Nutrient Dynamics of Summer Peanut (*Arachis hypogaea* L.) Through Use of Polythene Mulch, Hydrogel, and Nutrient Management." *Communications in Soil Science and Plant Analysis* 48, no. 5: 549–564. https://doi.org/10.1080/00103624.2016.1269792.

Kaya, Y., S. Jocic, and D. Miladinovic. 2012. "Sunflower." In *Technological Innovations in Major World Oil Crops, Volume 1: Breeding*, edited by S. K. Gupta, 85–129. New York, NY, USA: Springer. https://doi.org/10.1007/978-1-4614-0356-2_4.

Kencharaddi, H. G., P. G. Suresha, C. D. Soregaon, and A. Kumar. 2024. "Breeding and Molecular Approaches for Drought-Resilient Crops." In *Climate-Resilient Agriculture*, 227–265. Palm Bay, Florida, USA: Apple Academic Press.

Korada, R. R., S. K. Naskar, and S. Edison. 2010. "Insect Pests and Their Management in Yam Production and Storage: A World Review." *International Journal of Pest Management* 56, no. 4: 337–349. https://doi.org/10.1080/09670874.2010.500406.

Krishnan, P., B. Ramakrishnan, R. K. Raja, and V. R. Reddy. 2011. "High-Temperature Effects on Rice Growth, Yield, and Grain Quality." *Advances in Agronomy* 111: 87–206. https://doi.org/10.1016/B978-0-12-387689-8.00004-7.

Kumar, K. C., S. Maitra, T. Shankar, M. Panda, and L. Sagar. 2022. "Growth and Productivity of Sesame (*Sesamum indicum* L.) as Influenced by Spacing and Nitrogen Levels." *Crop Research* 57, no. 3: 190–194. https://doi.org/10.31830/2454-1761.2022.029.

Kusse, K., G. Ermias, and D. Darcho. 2022. “A Value Chain Analysis of Sesame (*Sesame indicum* L.) in South Omo Zone, Southern Ethiopia.” *Applied Studies in Agribusiness and Commerce* 16, no. 1: 5–14. https://doi.org/10.19041/APSTRACT/2022/1/1.

Lal, R. 2001. “Soil Degradation by Erosion.” *Land Degradation & Development* 12, no. 6: 519–539. https://doi.org/10.1002/ldr.472.

Leal Filho, W. 2010. *The Economic, Social and Political Elements of Climate Change*. Berlin, Germany: Springer Science & Business Media.

Low, J., J. Lynam, B. Lemaga, et al. 2009. “Sweetpotato in Sub-Saharan Africa.” In *The Sweetpotato*, 359–390. Dordrecht, Netherlands: Springer. https://doi.org/10.1007/978-1-4020-9475-0_16.

Mabhaudhi, T., T. P. Chibarabada, V. G. P. Chimonyo, et al. 2018. “Mainstreaming Underutilized Indigenous and Traditional Crops Into Food Systems: A South African Perspective.” *Sustainability* 11, no. 1: 172. https://doi.org/10.3390/su11010172.

Mabhaudhi, T., T. P. Chibarabada, and A. T. Modi. 2018. “Nutritional Water Productivity of Selected Sweet Potato Cultivars (*Ipomoea batatas* L.).” In *International Horticultural Congress IHC2018: International Symposium on Water and Nutrient Relations and Management of Horticultural Crops*, 295–302. Istanbul, Turkey: Acta Horticulturae. https://doi.org/10.17660/ActaHortic.2019.1253.39.

Mabhaudhi, T., V. G. P. Chimonyo, T. P. Chibarabada, and A. T. Modi. 2017. “Developing a Roadmap for Improving Neglected and Underutilized Crops: A Case Study of South Africa.” *Frontiers in Plant Science* 8: 2143. https://doi.org/10.3389/fpls.2017.02143.

Mabhaudhi, T., V. G. P. Chimonyo, S. Hlahla, et al. 2019. “Prospects of Orphan Crops in Climate Change.” *Planta* 250: 695–708. https://doi.org/10.1007/s00425-019-03129-y.

Matías, J., M. J. Rodríguez, A. Carrillo-Vico, et al. 2024. “From ‘Farm to Fork’: Exploring the Potential of Nutrient-Rich and Stress-Resilient Emergent Crops for Sustainable and Healthy Food in the Mediterranean Region in the Face of Climate Change Challenges.” *Plants* 13, no. 14: 1914. https://doi.org/10.3390/plants13141914.

Meena, R. P., V. Karnam, H. T. Sujatha, S. C. Tripathi, and G. Singh. 2024. “Practical Approaches to Enhance Water Productivity at the Farm Level in Asia: A Review.” *Irrigation and Drainage* 73, no. 2: 770–793. https://doi.org/10.1002/ird.2891.

Meldrum, G., and S. Padulosi. 2017. “Neglected No More: Leveraging Underutilized Crops to Address Global Challenges.” In *Routledge Handbook of Agricultural Biodiversity*, 298–310. Abingdon, Oxfordshire, United Kingdom: Routledge.

Mergoum, M., S. Sapkota, A. E. A. ElDoliefy, et al. 2019. “Triticale (× Triticosecale Wittmack) Breeding.” *Advances in Plant Breeding Strategies: Cereals* 5: 405–451. https://doi.org/10.1007/978-3-030-23108-8_11.

Morton, J. F. 2007. “The Impact of Climate Change on Smallholder and Subsistence Agriculture.” *Proceedings of the National Academy of Sciences of the United States of America* 104, no. 50: 19680–19685.

Mrabet, R. 2002. “Wheat Yield and Water Use Efficiency Under Contrasting Residue and Tillage Management Systems in a Semiarid Area of Morocco.” *Experimental Agriculture* 38, no. 2: 237–248. https://doi.org/10.1017/S0014479702000285.

Mudau, F. N., V. G. P. Chimonyo, A. T. Modi, and T. Mabhaudhi. 2022. “Neglected and Underutilised Crops: A Systematic Review of Their Potential as Food and Herbal Medicinal Crops in South Africa.” *Frontiers in Pharmacology* 12: 809866. https://doi.org/10.3389/fphar.2021.809866.

Mustafa, M. A., T. Mabhaudhi, and F. Massawe. 2021. “Building a Resilient and Sustainable Food System in a Changing World—A Case for Climate-Smart and Nutrient Dense Crops.” *Global Food Security-Agriculture Policy Economics and Environment* 28: 100477. https://doi.org/10.1016/j.gfs.2020.100477.

Ndlovu, M., P. Scheelbeek, M. Ngidi, and T. Mabhaudhi. 2024. “Underutilized Crops for Diverse, Resilient and Healthy Agri-Food Systems: A Systematic Review of Sub-Saharan Africa.” *Frontiers in Sustainable Food Systems* 8: 1–20. https://doi.org/10.3389/fsufs.2024.1498402.

Nehra, S., R. K. Gothwal, A. K. Varshney, et al. 2021. “Biomanagement of *Fusarium* spp. Associated With Pulse Crops.” In *Food Security and Plant Disease Management*, 423–452. Elsevier. https://doi.org/10.1016/B978-0-12-821843-3.00010-6.

Ngailo, S., H. Shimelis, J. Sibiya, and K. Mtunda. 2013. “Sweet Potato Breeding for Resistance to Sweet Potato Virus Disease and Improved Yield: Progress and Challenges.” *African Journal of Agricultural Research* 8, no. 25: 3202–3215. https://doi.org/10.5897/AJAR12.1991.

Ober, E. S., and A. Rajabi. 2010. “Abiotic Stress in Sugar Beet.” *Sugar Tech* 12: 294–298.

Okello, D. K., A. N. Kaaya, J. Bisikwa, M. Were, and H. K. Oloka. 2010. *Management of Aflatoxins in Groundnuts: A Manual for Farmers, Processors, Traders and Consumers in Uganda*. Entebbe, Uganda: National Agricultural Research Organization.

Oweis, T., A. Hachum, and M. Pala. 2004. “Water Use Efficiency of Winter-Sown Chickpea Under Supplemental Irrigation in a Mediterranean Environment.” *Agricultural Water Management* 66, no. 2: 163–179. https://doi.org/10.1016/j.agwat.2003.10.006.

Padulosi, S., J. Thompson, and P. G. Rudebjer. 2013. “Fighting Poverty, Hunger and Malnutrition With Neglected and Underutilized Species: Needs, Challenges and the Way Forward.” IBSN: 978-92-9043-922-5. 204. Rome, Italy: Bioversity International.

Palombi, L., and R. Sessa. 2013. *Climate-Smart Agriculture: Sourcebook*. 570. Rome, Italy: Food and Agriculture Organization of the United Nations (FAO). https://openknowledge.fao.org/server/api/core/bitstreams/b21f2087-f398-4718-8461-b92afc82e617/content.

Pandey, R. K., J. W. Maranville, and M. M. Chetima. 2001. “Tropical Wheat Response to Irrigation and Nitrogen in a Sahelian Environment. II. Biomass Accumulation, Nitrogen Uptake and Water Extraction.” *European Journal of Agronomy* 15, no. 2: 107–118. https://doi.org/10.1016/S1161-0301(01)00097-1.

Panella, L., S. R. Kaffka, R. T. Lewellen, J. Mitchell McGrath, M. S. Metzger, and C. A. Strausbaugh. 2014. “Sugarbeet.” *Yield Gains in Major US Field Crops* 33: 357–395. https://doi.org/10.2135/cssaspecpub33.c13.

Pingali, P. L. 2012. “Green Revolution: Impacts, Limits, and the Path Ahead.” *Proceedings of the National Academy of Sciences of the United States of America* 109, no. 31: 12302–12308. https://doi.org/10.1073/pnas.0912953109.

Popoola, J., O. Ojuederie, C. Omonhinmin, and A. Adegbite. 2019. “Neglected and Underutilized Legume Crops: Improvement and Future Prospects.” In *Recent Advances in Grain Crops Research*. London, United Kingdom: IntechOpen.

Porter, J. R., and M. Gawith. 1999. “Temperatures and the Growth and Development of Wheat: A Review.” *European Journal of Agronomy* 10, no. 1: 23–36. https://doi.org/10.1016/S1161-0301(98)00047-1.

Prasad, P. V. V., K. J. Boote, and L. H. Allen Jr. 2006. “Adverse High Temperature Effects on Pollen Viability, Seed-Set, Seed Yield and Harvest Index of Grain-Sorghum [*Sorghum bicolor* (L.) Moench] Are More Severe at Elevated Carbon Dioxide due to Higher Tissue Temperatures.” *Agricultural and Forest Meteorology* 139, no. 3–4: 237–251. https://doi.org/10.1016/j.agrformet.2006.07.003.

Ravi, V., P. Vikramaditya, M. Nedunchezhiyan, et al. 2021. “Advances in the Production Technologies of Taro in India.” In *Promotion of Underutilized Taro for Sustainable Biodiversity and Nutrition Security in SAARC Countries*, vol. 281, 148. Dhaka, Bangladesh: NARENDRA PUBLISHING HOUSE.

Ravisankar, N., M. Balakrishnan, S. K. Ambast, R. C. Srivastava, N. Bommayasamy, and T. Subramani. 2014. "Influence of Irrigation and Crop Residue Mulching on Yield and Water Productivity of Table Purpose Groundnut (*Arachis hypogaea*) in Humid Tropical Island." *Legume Research—An International Journal* 37, no. 2: 195–200.

Ray, L. I. P., K. Swetha, A. K. Singh, and N. J. Singh. 2023. "Water Productivity of Major Pulses—A Review." *Agricultural Water Management* 281: 108249. https://doi.org/10.1016/j.agwat.2023.108249.

Reddy, B. V. S., S. Ramesh, P. S. Reddy, B. Ramaiah, M. Salimath, and R. Kachapur. 2005. "Sweet Sorghum—A Potential Alternate Raw Material for Bio-Ethanol and Bio-Energy." *International Sorghum and Millets Newsletter* 46: 79–86.

Rondanini, D., R. Savin, and A. J. Hall. 2003. "Dynamics of Fruit Growth and Oil Quality of Sunflower (*Helianthus annuus* L.) Exposed to Brief Intervals of High Temperature During Grain Filling." *Field Crops Research* 83, no. 1: 79–90. https://doi.org/10.1016/S0378-4290(03)00064-9.

Rosero, A., L. Granda, J. A. Berdugo-Cely, O. Šamajová, J. Šamaj, and R. Cerkal. 2020. "A Dual Strategy of Breeding for Drought Tolerance and Introducing Drought-Tolerant, Underutilized Crops Into Production Systems to Enhance Their Resilience to Water Deficiency." *Plants* 9, no. 10: 1263. https://doi.org/10.3390/plants9101263.

Rubiales, D., and M. Fernández-Aparicio. 2012. "Innovations in Parasitic Weeds Management in Legume Crops. A Review." *Agronomy for Sustainable Development* 32: 433–449. https://doi.org/10.1007/s13593-011-0045-x.

Saini, K. S., and N. S. Brar. 2018. "Crop and Water Productivity of Sugarbeet (*Beta vulgaris*) Under Different Planting Methods and Irrigation Schedules." *Agricultural Research* 7: 93–97. https://doi.org/10.1007/s40003-018-0294-x.

Sala, C. A., M. Bulos, E. Altieri, and M. L. Ramos. 2012. "Sunflower: Improving Crop Productivity and Abiotic Stress Tolerance." *Improving Crop Resistance to Abiotic Stress*, 1203–1249. https://doi.org/10.1002/9783527632930.ch47.

Sánchez, B., A. Rasmussen, and J. R. Porter. 2014. "Temperatures and the Growth and Development of Maize and Rice: A Review." *Global Change Biology* 20, no. 2: 408–417. https://doi.org/10.1111/gcb.12389.

Saxena, M. C. 1980. "Recent Advances in Chickpea Agronomy." *Proceedings of the International Workshop on Chickpea Improvement* 28: 89–96.

Shahidi, F. 1990. *Canola and Rapeseed: Production, Chemistry, Nutrition, and Processing Technology*. Berlin, Germany: Springer Science & Business Media.

Sharma, K. K., S. R. Palakolanu, J. Bhattacharya, A. R. Shankhapal, and P. Bhatnagar-Mathur. 2022. "CRISPR for Accelerating Genetic Gains in Under-Utilized Crops of the Drylands: Progress and Prospects." *Frontiers in Genetics* 13: 999207. https://doi.org/10.3389/fgene.2022.999207.

Siddique, K., and X. Li. 2019. "The Potentials of Future Smart Food for Mountain Agriculture Achieving Zero Hunger: Nutrition, Climate-Resilient, Economic and Social Benefits." In *Mountain Agriculture: Opportunities for Harnessing Zero Hunger in Asia*, 45–55. Rome, Italy: Food and Agriculture Organization of the United Nations (FAO).

Siddique, K. H. M., X. Li, and K. Gruber. 2021. "Rediscovering Asia's Forgotten Crops to Fight Chronic and Hidden Hunger." *Nature Plants* 7, no. 2: 116–122. https://doi.org/10.1038/s41477-021-00850-z.

Singh, V., and N. Nimbkar. 2006. "Safflower (*Carthamus tinctorius* L.). In Chapter 6." In *Genetic. Resources, Chromosome Engineering, and Crop Improvement: Oilseed Crops*, 167–194. Boca Raton, Florida, USA: CRC Press.

Stevanato, P., C. Chiodi, C. Broccanello, et al. 2019. "Sustainability of the Sugar Beet Crop." *Sugar Tech* 21: 703–716. https://doi.org/10.1007/s12355-019-00734-9.

Sunitha, S., J. George, G. Suja, V. Ravi, S. Haripriya, and J. Sreekumar. 2018. "Irrigation Schedule for Maximum Corm Yield and Water Productivity in Elephant Foot Yam (*Amorphophallus paeoniifolius*)." *Indian Journal of Agricultural Sciences* 88, no. 7: 1013–1017. https://doi.org/10.56093/ijas.v88i7.81538.

Sunitha, S., and J. Sreekumar. 2023. "Water Productivity and Crop Water Production Function of Taro (*Colocasia esculenta* L. Schott) Under Different Irrigation Regimes." *Journal of Root Crops* 49, no. 1: 35–38.

Sweetingham, M., and R. Kingwell. 2008. "Lupins-reflections and future possibilities." In *2008 'Lupins for Health and Wealth' Proceedings of the 12th International Lupin Conference, 14–18 Sept. 2008, Fremantle, Western Australia*, edited by J. A. Palta and J. B. Berger. Canterbury, New Zealand: International Lupin Association.

Taaime, N., S. Rafik, K. El Mejahed, et al. 2023. "Worldwide Development of Agronomic Management Practices for Quinoa Cultivation: A Systematic Review." *Frontiers in Agronomy* 5: 1215441. https://doi.org/10.3389/fagro.2023.1215441.

Teklu, D. H., H. Shimelis, A. Tesfaye, and S. Abady. 2021. "Appraisal of the Sesame Production Opportunities and Constraints, and Farmer-Preferred Varieties and Traits, in Eastern and Southwestern Ethiopia." *Sustainability* 13, no. 20: 11202. https://doi.org/10.3390/su132011202.

Terán, H., M. Lema, D. Webster, and S. P. Singh. 2009. "75 Years of Breeding Pinto Bean for Resistance to Diseases in the United States." *Euphytica* 167, no. 3: 341–351. https://doi.org/10.1007/s10681-009-9892-9.

Tuong, T. P., B. A. M. Bouman, and M. Mortimer. 2005. "More Rice, Less Water—Integrated Approaches for Increasing Water Productivity in Irrigated Rice-Based Systems in Asia." *Plant Production Science* 8, no. 3: 231–241.

USDA. 2024. "The Vision for Adapted Crops and Soils (VACS)." Washington, D.C., USA: United States Department of Agriculture (USDA). https://www.state.gov/vacs-champions/.

Varshney, R. K., M. Thudi, S. N. Nayak, et al. 2014. "Genetic Dissection of Drought Tolerance in Chickpea (*Cicer arietinum* L.)." *Theoretical and Applied Genetics* 127: 445–462. https://doi.org/10.1007/s00122-013-2230-6.

Yadav, S. S., A. H. Rizvi, M. Manohar, et al. 2007. "Lentil Growers and Production Systems Around the World." In *Lentil: An Ancient Crop for Modern Times*, edited by S. S. Yadav, D. McNeil, and P. C. Stevenson, 415–442. Dordrecht, Netherlands: Springer. https://doi.org/10.1007/978-1-4020-6313-8_23.

Yang, X., J. Xiong, T. Du, et al. 2024. "Diversifying Crop Rotation Increases Food Production, Reduces Net Greenhouse Gas Emissions and Improves Soil Health." *Nature Communications* 15, no. 1: 198. https://doi.org/10.1038/s41467-023-44464-9.

Supporting Information

Additional supporting information can be found online in the Supporting Information section.