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Diversifying agrifood systems to ensure global food security following the Russia–Ukraine crisis

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The recent Russia–Ukraine conflict has raised significant concerns about global food security, leaving many countries with restricted access to imported staple food crops, particularly wheat and sunflower oil, sending food prices soaring with other adverse consequences in the food supply chain. This detrimental effect is particularly prominent for low-income countries relying on grain imports, with record-high food prices and inflation affecting their livelihoods. This review discusses the role of Russia and Ukraine in the global food system and the impact of the Russia–Ukraine conflict on food security. It also highlights how diversifying four areas of agrifood systems—markets, production, crops, and technology can contribute to achieving food supply chain resilience for future food security and sustainability.

KEYWORDS

Russia–Ukraine conflict, food security, agrifood systems, diversification, sustainable intensification

1. Introduction

In the past 2 years, global issues such as climate change, the COVID-19 pandemic, and the Russia–Ukraine conflict have taken the spotlight, with reports and discussions around these events flooding the media. This has led to intense pressure on socioeconomics, healthcare, and food systems in a short time. Confronting us are direct consequences of these global crises on the agrifood systems, particularly from the Russia–Ukraine conflict, throwing food security issues into the limelight. Ukraine and Russia are in the top three global exporters of various staple foods, including wheat, barley, maize, rapeseed, and sunflower (FAO, 2022a). Disruptions to their exports are having strong ripple effects on the global food market and concerns for food security (Behnassi and El Haiba, 2022).

The Russia–Ukraine conflict directly impacts global agrifood systems through trade, production, and prices (FAO et al., 2022). The FAO estimates that the shortfall in grain and sunflower seeds exports from Ukraine and Russia will increase international wheat prices by between 8.75% (moderate case) and 21.5% (severe case) in 2022/23. Countries hardest

hit by the reduction in Ukraine and Russia's food exports in terms of physical supply are those relying heavily on wheat and wheat products imports—the Middle East and North Africa, developing countries in Europe, and sub-Saharan Africa (World Bank Group, 2022), therefore impeding the efforts to eradicate malnutrition and hunger by 2030 which is the focus in the second goal of the United Nation's 17 Sustainable Development Goals (SDG Target 2, Zero Hunger). This will be pronounced in net food-importing developing countries (Figure 1), i.e., the world's poorest countries (UNCTAD, 2022), concentrated in sub-Saharan African nations that imported 85% of national food requirements in 2016–2018. The Russia–Ukraine conflict has caused a shortfall of at least 30 million tons of food in sub-Saharan African nations (African Development Bank Group, 2022), as well as other regions (South Asia, the Middle East, North Africa, Latin America and the Caribbean, and East Asia) that were already facing food security problems (UNCTAD, 2021).

This food crisis at a global scale was not unexpected. Global food crises have occurred in the past, incurred by: (1) high oil prices in 2007–2008, (2) increased food demand in emerging economies (Mittal, 2009; Headey and Fan, 2010), (3) extreme weather incidents such as drought, floods and storms in 2010–2011 in many grain-producing countries (e.g., China, Australia, Argentina, Russia, and Ukraine) (Johnstone and Mazo, 2011; Werrell et al., 2013), and more recently, (4) the COVID-19 pandemic causing global disruptions in the food supply chains (Hart et al., 2022; Pauw and Thurlow, 2022). If past global food crises have taught us anything, agrifood systems need to be restructured to make them more resilient and strategies put in place to manage such crises (Pellegrini and Fernández, 2018).

To this end, this review highlights the impact of the current international crisis on agrifood systems. We first discuss the role of Russia and Ukraine as the main exporters of cereal grains and oilseed crops, followed by a discussion of the impact of the conflict on global agrifood systems. We then highlight the over-reliance on a few countries for a large portion of our major food staples and its potential consequences for global food security. Lastly, we offer suggestions on several aspects of diversification within the agrifood systems to enhance global food security and nutrition in this challenging time.

2. Agrifood systems

Agrifood systems comprise all players and components in producing agricultural food products, such as crops, livestock, fisheries, forestry, and aquaculture, and non-agricultural food products, such as synthetic meat. The production, storage, processing, distribution, consumption, and disposal of these products support human food consumption and sustain life (FAO, 2021; United Nations 2021 Food Systems Summit, 2021). Agrifood systems also encompass non-food products that are agriculturally based, such as textiles, biofuels, fiberglass, and cosmetics, but these are outside the context of our current discussion. The 2020 FAO statistics record shows that the total gross value of agricultural production (crop and livestock) worldwide equated to USD 4.79 trillion (FAOSTAT, 2022). The main players in the global agrifood systems are those that influence international food prices and

demand through various agrifood sectors. These include major exporters of food commodities, agriculture companies involved in agrochemicals, commercial seed suppliers, farm equipment suppliers, food processors, retailers, and others (ETC Group, 2022). We discuss how we should not over-rely on major food exporters and propose diversification as a sustainable way to achieve agrifood system resilience.

3. Role of the Russian federation and Ukraine in the agrifood systems

Russia and Ukraine are ranked 11 and 55 in the world economy in terms of GDP (US\$), with their top export commodities being petroleum and agriculture, respectively (OEC, 2022). Both countries are global contributors to a substantial share of agricultural commodities, including raw materials for fertilizers, and are key exporters of cereal and oilseed food crops (World Bank Group, 2022). In 2020, Russia ranked number one in wheat exports, and Ukraine ranked number one in seed oil exports (OEC, 2022). Figure 2 illustrates the economic contributions of exported commodities by Russia and Ukraine in 2021 (UN Comtrade Database Intelligence, 2021).

4. Impact of the Russia–Ukraine conflict on agrifood systems

4.1. Food export bans and restrictions

The Russia–Ukraine conflict has produced shocks in the commodity markets for food, feed, fertilizers, and energy (OECD, 2022a) and impacted agrifood systems in many areas. As of early April 2022, 16 countries had imposed food commodities export bans following the escalation of the Russia–Ukraine conflict, equating to about 17% of total calories traded globally (Glauber et al., 2022). This is to ensure a sufficient supply of food within their own countries. With the closure of main Ukrainian ports at the Black Sea and the effects of multiple global economic sanctions imposed on Russia, both countries have evidently contributed to the largest percentage of food exports restrictions, equating to 42% of total calories (European Parliament Think Tank, 2022; Glauber et al., 2022). Other countries introduced export bans on various agricultural products, such as palm oil from Indonesia (Office of Assistant to Deputy Cabinet Secretary for State Documents and Translation, 2022) and grain products from Turkey, Kyrgyzstan, and Kazakhstan (CGIAR, 2022; Donley, 2022).

While some of these export bans were temporary and have been lifted, this exercise could potentially generate a domino effect with other exporting countries then implementing their own import/export restrictions in response to deviations in food prices. This will further destabilize the food supply in global markets with almost immediate inflation of food prices, severely affecting Central Asian countries and North African countries which rely on imports of wheat and maize, while India, Pakistan, and Bangladesh rely on imports of vegetable oils (Giordani et al., 2016; Glauber et al., 2022).

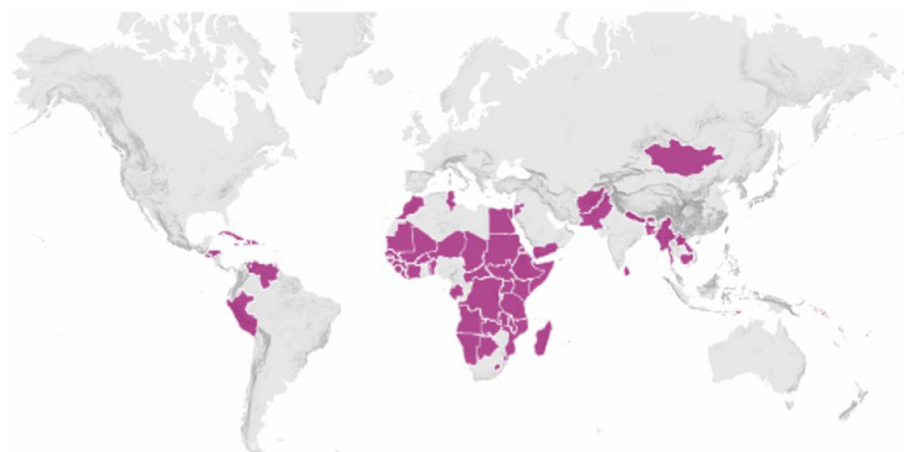


FIGURE 1

Net Food Importing Developing Countries (NFIC) vulnerable to food system disruption due to exogenous events such as the Russia–Ukraine conflict including sub-Saharan Africa, South Asia, the Middle East, North Africa, Latin America and the Caribbean, and East Asia (FAO, 2022b) (Figure re-produced with permission from FAO Copyright Office).

4.2. Food price hike

The rise in food prices is not solely a direct consequence of the Russia–Ukraine conflict, as an increasing trend has been apparent since 2020, but 2022 saw a “giant leap” in the food price index (Figure 3) (FAO, 2022c; Weersink and von Massow, 2022).

The increasing trend in food prices from 2020 to early 2022 is mainly shaped by the COVID-19 pandemic, with travel restrictions and lockdowns within and outside countries causing farm production to slow down, creating bottlenecks in the food supply chain [OECD Policy Responses to Coronavirus (COVID-19), 2020]. Other causes of food price hikes include the upward shift in food, feed, and fuel demand as the world gradually recovered from the pandemic and some crop production losses due to unfavorable weather patterns in Brazil and the USA (Sova and Man, 2021). The conflict in Ukraine during the first quarter of 2022 held back the reduction of food and energy inflation, thus increasing the global commodity prices in 2022–2023 (OECD, 2022b).

In the longer term, food prices are predicted to continue to increase even after the Russia–Ukraine conflict ends, as we continue to face reduced crop production due to volatile weather patterns induced by climate change (Cowling et al., 2019; Sultan et al., 2019; Anderson et al., 2020), such as the recent extreme heat, drought and flood conditions in Europe, the USA, the Horn of Africa and China, among others (Lodewick, 2022; WFP, 2022). Models have also predicted yield declines of up to 21.5% in maize on the US Great Plains due to erratic climate patterns (Irmak et al., 2022) and a reduction of up to 12.5% in wheat production in South Africa due to extreme heat (Shew et al., 2020). Moreover, studies have shown that extreme weather events are likely to occur more frequently and will be more intense in the future, directly and indirectly impacting crop yields and further threatening global agrifood systems and supplies with long-term implications for increasing food prices (Diffenbaugh et al., 2018).

4.3. Threat to food security

According to the Bill and Melinda Gates Foundation (BMGF) Goalkeepers Report (Bill and Melinda Gates Foundation Goalkeepers Report 2022, 2022), achieving SDG target 2 (Zero Hunger) by 2030 is too ambitious. Yet understanding the current status of global agrifood systems and food security is critical in facilitating the eradication of hunger (FAO et al., 2022).

In 2021, ~193 million people across 53 countries faced acute food insecurity at crisis level or worse (IPC/CH Phase 3 or above; 1 = minimal/non, 5 = catastrophe/famine) (Integrated Food Security Phase Classification, 2022), almost doubling from 2016 levels, with a concerning figure of 570,000 people categorized as in catastrophe conditions (IPC/CH Phase 5) in Ethiopia, South Sudan, southern Madagascar, Yemen, Afghanistan, and Somalia, where conflict is the primary driver of severe food insecurity (Global Report on Food Crises, 2022; WFP and FAO, 2022) because it disrupted agriculture-based livelihoods, restricted food access, impeded humanitarian operations and displaced populations (mainly smallholder farmers).

Even before the conflict in Russia–Ukraine, ongoing social unrest in several countries concentrated in Eurasia, namely Afghanistan, Bangladesh, Iraq, the Syrian Arab Republic, Yemen, and Ukraine, resulted in as many as 52.8 million people experiencing food insecurity at a crisis level (IPC Phase 3 or above) in 2021, up from 30.9 million in 2016, with nearly 16.8 million people displaced due to conflict (Global Report on Food Crises, 2022). That this is a continuous issue is supported by the findings that in 2014 food insecurity across sub-Saharan Africa, particularly in South Sudan and Nigeria, was driven by conflict (Anderson et al., 2021).

Based on FAO estimations, the Russia–Ukraine conflict will increase the number of undernourished people globally by 13.1 million in a worst-case scenario, added to the current 733.9 million undernourished people not impacted by the onset of the

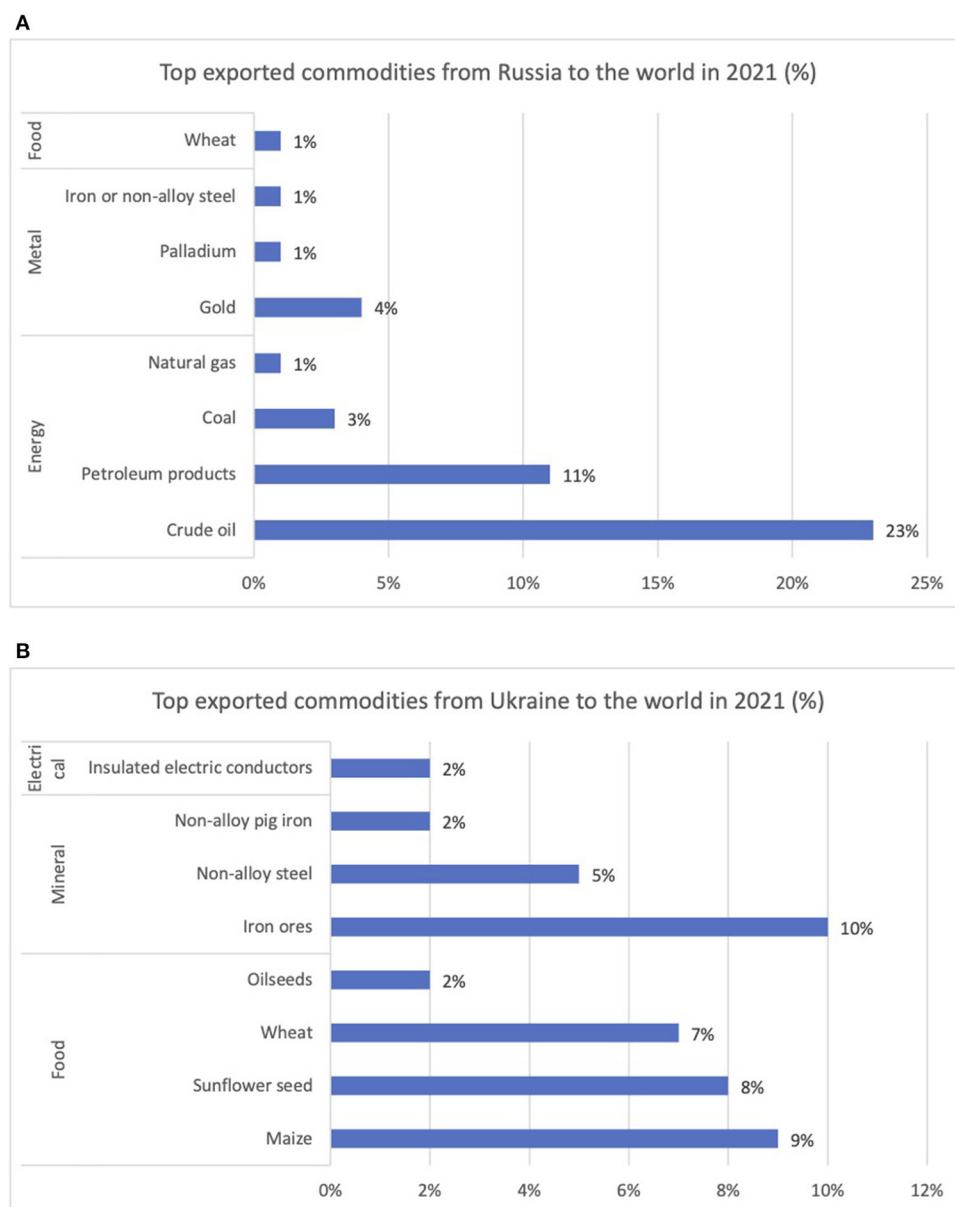


FIGURE 2 Top exported commodities in (A) Russia, and (B) Ukraine in 2021 (UN Comtrade Database Intelligence, 2021).

conflict (FAO et al., 2022). Sub-Saharan Africa, the Middle East, and North Africa are the most vulnerable population groups impacted by the Ukraine conflict (FAO et al., 2022). Adding to the malnutrition problem, food insecurity positively correlates with social unrest, particularly in developing countries, leading to further insecurity (Arezki and Bruckner, 2011; Weinberg and Bakker, 2015; Soffiantini, 2020).

4.4. Livelihood struggle among the rural poor

The Russia–Ukraine crisis has impacted poor and rural households due to fuel, food, and fertilizer price hikes. Countries

such as Kenya (Breisinger et al., 2022), Egypt (Abay et al., 2022), Bangladesh (Diao et al., 2022b), and Ethiopia (Diao et al., 2022a) have witnessed declines in food consumption and diet quality. The increase in fertilizer prices also caused a heavy toll on local farmers in these countries, whose livelihoods depend on agriculture. If farmers reduce fertilizer use due to price hikes, their production often declines, impacting rural household incomes.

Typically, most farmers in developing countries in East Asia and the Pacific, South Asia, and sub-Saharan Africa are smallholders (farm owners operating agricultural land areas <2 ha). They account for 84% of global farms, contributing about 35% of the world’s food (Ricciardi et al., 2018; Lowder et al., 2021). These smallholder farmers often live in remote areas and produce a wide variety of foods in addition to the main crop, but often

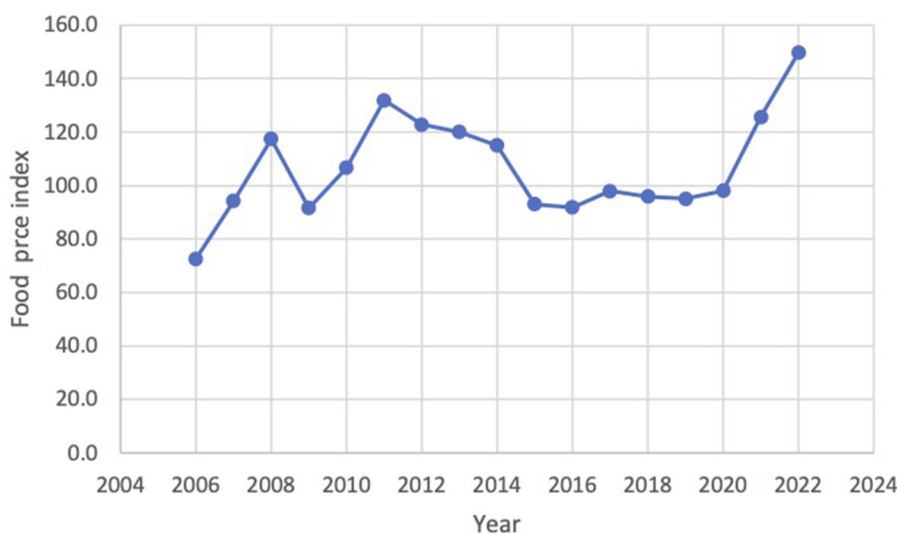


FIGURE 3
Annual FAO food price indices from 2006–2022 (FAO, 2022c).

with low productivity (Rapsomanikis, 2015). They are vulnerable to food insecurity due to sociodemographic factors (e.g., family size, education level of family members, farming experience) and have low resilience to changing circumstances, such as weather shocks and pest and disease outbreaks, as reflected in household surveys conducted in Central America (Guatemala and Honduras) (Alpizar et al., 2020) and Africa (Madagascar) (Harvey et al., 2014).

Using satellite data images of croplands in Ukraine, studying the impact of the conflict on winter wheat production across 2019–2021, Deininger et al. (2022) revealed that smallholder farmers are the most vulnerable group. They own 60% of the agricultural land and have experienced the most severe output losses, perpetuated by agricultural resource shortages such as labor, seed, fertilizers, and pesticides.

5. Over-reliance on major food exporters/importers and inequalities in agrifood business

Although the Russia–Ukraine conflict is not the sole cause of the current global food crisis, it has highlighted deeply inequitable agrifood systems (Hawkes et al., 2022). One of the inequities is the over-reliance on major food exporters, driven by the high global demand and reliance on a few major cereal crops, such as wheat, maize, and rice, much of which are consumed by populations in developing countries, and maize is also highly used for feed and biofuel applications (Figure 4).

Often, global staple food producers are concentrated in a small number of countries. For example, for the top staple commodities based on gross production value—rice, maize, wheat, and soybean—the biggest net producers and exporters are China, India, the USA, Brazil, and Russia (FAOSTAT, 2022) (Figure 5). The top rice-producing countries are China and India, producing 50% of global rice production. The top maize-producing countries

are the USA, China, and Brazil, producing 60% of global maize production. China, India, Russia, and the USA produce 49.6% of the world's wheat, while Brazil and the USA produce 66.3% of the world's soybean (FAOSTAT, 2022). The Middle Eastern, North African, and East Asian regions are the largest net importers of these commodities, yet also have the highest rates of food insecurity (OECD/FAO, 2022b).

Major agrifood players are key in ensuring global food security through international trade. However, models of the relationships between population growth, food production, and trade dynamics have shown that over-dependence on food imports impairs global food security (Suweis et al., 2015). Low-income food-deficit regions, such as Africa, the Middle East, and Latin America, are most vulnerable to price shocks in food trade and least able to protect themselves against domestic food production shocks (Grassia et al., 2022). Worse still, the UN International Labor Organization said in its 2021 report that people in these countries live with much lower rates of social welfare protection. For example, Africa has the lowest level, with 17.4% of the population having access to social welfare protection, compared to Europe and Central Asia, where 84.0% of the population have access to social welfare protection (International Labour Organization, 2021). Consumers in low-income countries spend relatively more on food (40% of spending in sub-Saharan Africa) than high-income countries (17% in advanced economies) (Bogmans et al., 2022), such that food price variabilities potentially result in poor people being unable to afford enough, presenting a conundrum for these affected countries because they increasingly need to import food to meet the needs of rapid population growth (van Berkum, 2021).

The Russia–Ukraine conflict has exposed inequalities in the international agribusiness sector. In the last decades, there has been a trend toward consolidation of corporations that supply food and agricultural inputs through large-scale mergers such as Kraft and Heinz, Dow and Dupont, Bayer and Monsanto, with each company's worth reaching over US\$60–100 billion after

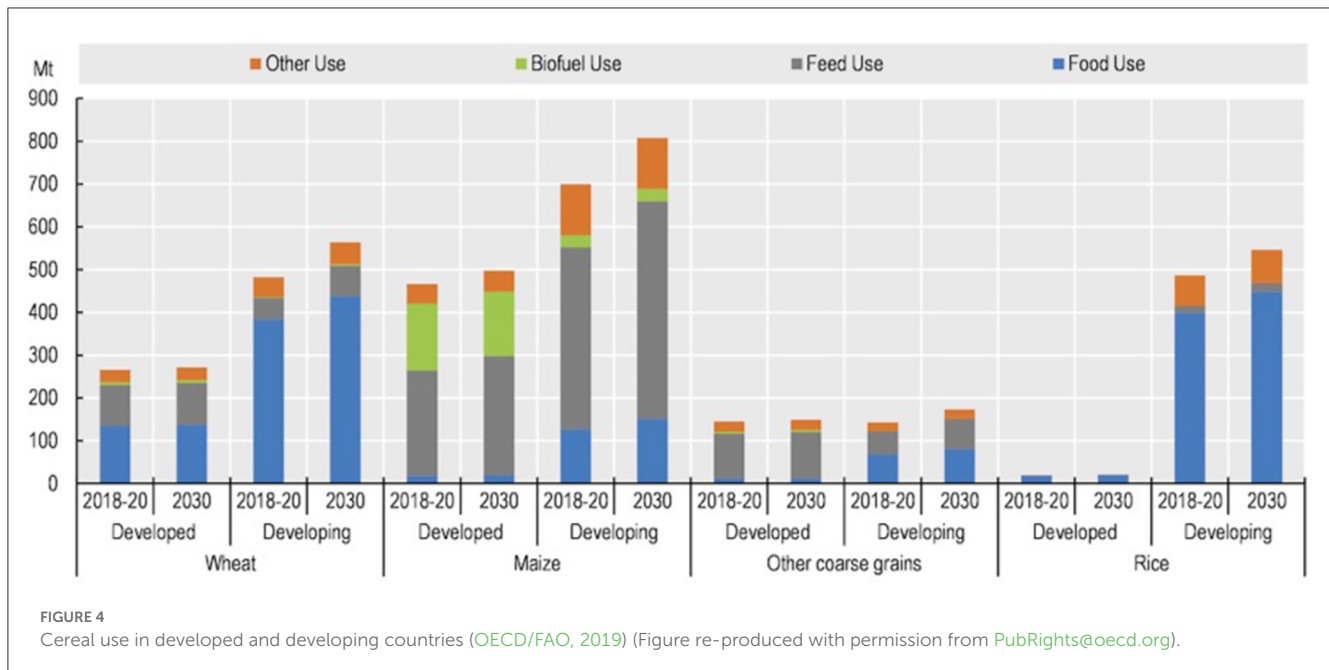


FIGURE 4
Cereal use in developed and developing countries (OECD/FAO, 2019) (Figure re-produced with permission from PubRights@oecd.org).

merging (Clapp, 2022). These companies play a crucial role in global food supply, at the same time influencing the volatility of the international price of food commodities. In the agrochemical industry, the top four companies—Syngenta Group (China), Bayer (Germany), BASF (Germany), and Corteva (USA) dominate 62% of the global agrochemical market, where Bayer and Corteva also control 40% of the global seed market (ETC Group, 2022).

6. Role of diversification in four aspects of agrifood systems

6.1. Market diversification

The projected increase in global food demand of 1.4% per annum over the coming decade, stimulated by a large growth in the world's population and *per capita* income (OECD/FAO, 2022a), will place tremendous pressure on major food exporters to ensure consistent agricultural outputs and to develop high resilience to various shocks. The main exporters of wheat and other staple products are sometimes major importers of the same crop. For example, Asia's top five wheat producers (China, India, Pakistan, Turkey, and Iran) contributed 332.94 Mt to global production, compared with 260.23 Mt in Europe in 2019. However, their wheat imports (74.19 Mt) exceeded their exports (6.61 Mt), attributed to the limited countries in Asia that meet the required growth conditions for bread wheat (Sendhil et al., 2022). However, with modern breeding technologies, many cereal crop varieties can withstand adverse climatic patterns, providing breakthroughs that allow crops to be grown outside their typical environments. For instance, high-yielding, heat-tolerant wheat varieties have been developed from large-scale field trials and germplasm screening in the Senegal River, a joint effort by ICARDA and the Swedish University of Agriculture (Bassi, 2017; Sall et al., 2018). Abandoned land in many developing countries could be used to cultivate staple

food crops that fit the region's ecology, despite originating from other geographic regions.

To minimize the global impact of the food crisis, it is critical to diversify the import/export sources of food crops. For example, New Zealand has recently diversified its avocado export markets from Australia, where it previously shipped 79% of its total exports in the last 5 years, to Asian countries such as Singapore, Hong Kong, and South Korea after a decline in Australia's import demand (F+B Tech, 2022; Piggott, 2022). This is a win-win situation for establishing food resilience where the exporting country retains its role as the food supplier while the importing country benefits from securing food products to meet domestic food demands. Singapore imports 90% of its food from more than 170 countries, with food items coming from geographically diverse regions; the country continues to identify new food sources as part of its strategy to ensure market diversification with constant food supply (Teng, 2020; Singapore's Food Supply, 2022). The FAO measurement of countries with multiple food trade partners to ensure food security and nutrition—using the dietary sourcing flexibility index (DSFI)—is an attractive approach to market diversification and minimizing the adverse impact of a food crisis. The DSFI index measures food supply diversity based on multiple sourcing pathways of food commodities, imports, and available stocks. Countries with high DSFI values, such as Israel, Lebanon, Norway, and the UK, have a high capacity to absorb shocks with multiple options for food suppliers coming from diverse trade partners and multiple commodities. This contrasts with countries such as Indonesia, Madagascar, Pakistan and the Republic of Moldova with limited trade partners and fewer food commodity options (FAO, 2021).

Food market diversification on the international front requires trade agreement policies between nations, with transparent, updated information provided to all nations regarding agricultural markets. For example, the Agricultural Market Information System (AMIS), comprising G20 members with additional major exporters and importers of agricultural commodities, makes concerted efforts



FIGURE 5 Import and export quantities (kilo tons) for the four major staple crops (wheat, rice, maize, and soybean) (FAOSTAT, 2022).

to enhance international food trade policy using real-time data of food markets to prevent price hikes (Hertel et al., 2021; Agricultural Market Information System, 2022). At the regional level, for

example, the project initiative “Agricultural Transformation and Market Integration in the ASEAN Region: Responding to Food Security and Inclusiveness Concerns (ATMI-ASEAN),” supported

by the International Food Policy Research Institute (IFPRI), addresses food security issues within the ASEAN region to increase smallholder farmer competitiveness in regional agrifood markets by identifying diverse crops with high impact value, with cooperation between agricultural stakeholders in member countries—Cambodia, Lao PDR, Myanmar, Viet Nam and the Philippines (Southeast Asian Regional Center for Graduate Study and Research in Agriculture, 2017). In addition, market diversification involves shifting part of the demand and supply for staples to non-staple foods such as fruits, vegetables, and pulses, considered high in protein and micronutrients, entering such food markets for a more balanced diet and nutritional outcomes (Pingali, 2015).

Another way to diversify food markets is to promote the production and commercialization of alternative foods sourced sustainably (e.g., plant-based foods). This approach has good health effects and diversity of flavors, tastes, and textures, increasing consumers' menu options and making food markets more resilient to price shocks. For example, consumers are receptive to blending wheat flour with cassava flour, indicating the potential use of minor crops as alternative foods (Owusu et al., 2017). Governments could provide funds to start-up companies involved in “ecologically friendly” food production or businesses involved in agricultural technologies to stimulate the demand for alternative crops, boosting the country's economy and supporting food security and healthy living.

Domesticating indigenous fruit tree species (IFTs), and herbaceous species within the broad traditional foods and medicinal plants can also be a good option to diversify food markets (Leakey, 2014; Leakey et al., 2022). We can achieve this by extending the food market and value chain to include nutrient-dense foods that fall under the radar of public attention, including neglected and underutilized species (NUS) and indigenous fruit tree species, such as *Strychnos madagascariensis* (fruit processed as flour) from Africa countries (Chemane et al., 2022) and *Garcinia andamanica* King (fruit suitable as a food additive) from Andaman Islands, India (Bohra et al., 2021). To increase the marketability of these alternative foods, attention should be drawn toward strengthening independent local and regional food systems. This can be achieved by providing a support network to farmers selling through a direct-to-consumer channel or in short food supply chains (SFSC) markets (Jarzebowski et al., 2020; Schreiber et al., 2022). For instance, policymakers ought to put into action the delivery of high-quality workflow for the value-added processing, storage and distribution of fresh products to local communities that can help farmers retain a larger portion of the retail value of food, and enhance resilience to shocks in the international supply chain (Enthoven and Van den Broeck, 2021).

6.2. Production diversification

Due to soaring costs, the Russia–Ukraine conflict has put immense pressure on farmers and supply chains relying on fertilizer, feed, and fuel. How we produce food crops has to be diversified as part of food sustainability strategies. Intensive

agriculture, driven by the Green Revolution in the mid-20th Century, emphasized monoculture, crop hybridization, and reliance on fertilizers and other agrochemicals that increased yield. However, these developments also resulted in increased reliance on international supply chains and had unintended impacts on natural resources, such as water and land, due to the heavy use of fertilizers and other agrochemicals (United Nations, 2004; Rosa et al., 2021; Soria-Lopez et al., 2022). In contrast, sustainable intensification in the 21st Century seeks to leverage on least agricultural inputs to achieve equal if not higher crop yield without incurring the environmental impact and further expansion of cropland (Pretty and Bharucha, 2014; Campanhola and Pandey, 2019). This involves using improved crops, regenerative agricultural methods, and diversified production and distribution systems. The concept of sustainable intensification was incepted by FAO in 2011 under the “Save and Grow” model, aiming to achieve food security through balancing increasing productivity and positive outcomes for the environment (Collette et al., 2011).

Diversification of agricultural practices, such as intercropping spatially or temporally, mixed farming with crop and livestock, adding organic material or beneficial microbes in the soil, and reduced tillage, has contributed to biodiversity conservation, improved soil fertility, enhanced nutrient cycling and water regulation, and improved pest control, decreasing the environmental burden without compromising crop yield (Tamburini et al., 2020; Yan et al., 2022). For example, intercropping systems with grain legumes such as pigeonpea (*Cajanus cajan*) or leguminous tree species such as fliricidia (*Gliricidia sepium*) in smallholder maize farming in Tanzania, East Africa, has shown that the grain yield, caloric and protein yields were not inferior to monoculture maize. The other benefit is the maize-pigeonpea intercrop requires a reduced land area to produce the same grain yields under drought and well-watered conditions (Renwick et al., 2020). Agroforestry tree and shrub species in semi-arid West African parklands in which forests areas were cleared for agriculture farming purposes have been shown to restore both soil fertility and health by providing rich organic biomass through the burial of ramial wood or small branches during forest management (Félix et al., 2018). Depending on the type of tree and shrub species, for example, legume tree *Leucaena leucocephala* and berry fruit tree Phalsa (*Grewia asiatica*), when utilized as an intercrop or rotational crop with different food crops including cereals, leguminous and oilseeds, would not only improve crop yield (Sileshi et al., 2011; Rathore et al., 2022) but provide far-reaching benefits for the farmers, environment and food security. Farm diversification among smallholder farmers in Bangladesh and Central Malawi, including alternative crops, livestock and aquaculture farming, has seen a significant shift toward diversified diets and high nutrient assimilation as these farmers consume their farm produce and improve their household income and food security (Mango et al., 2018; Rehan et al., 2021).

Simulation and modeling studies of sustainable intensification in the Brazilian Amazon basin have shown that, adding soybean cultivation to livestock production areas, has multiple environmental and yield benefits, increasing soybean production from 2022/2023 forecasted 144–162 Mt without deforestation and decreasing climate warming by up to 58% (Marin et al., 2022; USDA FAS, 2022). Cropping system diversification, for example,

rotational sequences of cereals/grasses such as rice and maize with legumes such as peas and mungbean in China, India, and Bangladesh, or mixtures of pea, oilseeds, and wheat in the Boreo-Nemoral region (Scandinavian or Northern Europe countries) have improved system productivity through higher crop resource use efficiencies with great potential for increasing nutrient levels and reducing carbon footprints (Lizarazo et al., 2020; Chai et al., 2021; Emran et al., 2022; Gora et al., 2022).

Integrated pest management (IPM) for crop protection also taps into diversified strategies to prevent, avoid or reduce pests using ecologically sound methods such as crop rotation, natural and biological controls, and host plant pest resistance or tolerance, and synergies between these strategies. One example is biofumigation by burying into the soil the natural glucosinolate sourced from plant members within the Brassicaceae family to suppress the pests (Richard et al., 2022). Another example of IPM is the control of the moth *Tuta absoluta*. This South American tomato pinworm pest severely destroys tomato production worldwide, using biological agents such as bacteria, fungi, nematodes, and predatory arthropods (Desneux et al., 2022). Recently, IPM technology (IPMT) has been proposed, which expands from IPM that incorporates the components of genetically engineered cultivar and biotechnology approaches that are relevant to today's agricultural setting with the focus on monitoring, identification, assessment, and prevention of pests with minimal environmental impacts using data-driven tools (Tanda, 2022). For example, the Intelligent and Integrated Pest and Disease Management (I2PDM) system was developed to capture the presence of plant pests such as thrips and whiteflies under a controlled environment setting, which greatly enhance the efficiency of plant disease monitoring (Rustia et al., 2022).

Smallholder farmers play an important role in supplying food globally (Terlau et al., 2019). All the positive outcomes of diversification described above cannot reach their full potential impacts in addressing global or regional food security without providing strong socio-economic support to smallholder farmers and ensuring that farming activities are enriching (Giller et al., 2021). There will also need to be a transformation in agronomy knowledge whereby on top of the hard sciences, integration of social science disciplines such as sociology, economics, and policy studies is embraced for future knowledge-based sustainable farming (Struik and Kuyper, 2017; Klerkx et al., 2019). Understanding farmers' difficulties in farm practices, with strong support from government agriculture agencies offering attractive subsidies, zero- to low-interest micro-financing, proper training and guidance, and close monitoring of agricultural outputs is essential (Epule, 2019). On the national front, strong support from the government through incentives, allowances, and subsidies to smallholder farmers to reinforce crop cultivation is an effective measure for household food security.

6.3. Crop diversification

For the past 60 years, human food sources that provide macronutrients such as energy, protein, and fat have primarily come from 50 crop commodities, including wheat, rice, maize,

barley, potatoes, and general vegetable and fruit commodities comprising <100 plant species (Khouri et al., 2014; Massawe et al., 2016; Shelef et al., 2017). With 7,039 known edible plant species recorded across 2,319 genera (Kew Gardens, 2020), there is still a large portion of edible plants that we could use for food diversification, including neglected and underutilized food crops (NUS) (Sogbohossou et al., 2018; Mustafa et al., 2019).

NUS currently have limited production and market values compared to major staples (Khouri et al., 2022). They have been nurtured as native crops agriculturally suited to local or regional climates and grown in domesticated forms or introduced centuries ago and are now established in their local environments. NUS are breeding candidates for advanced food crops with great economic potential (Mabhaudhi et al., 2019; Tirnaz et al., 2022). NUS cover a wide range of crop types, including cereals, roots and tubers, legumes, fruits and vegetables, seeds and spices, and were often traditionally grown by indigenous people and smallholder farmers as food for home consumption or a source of income at local markets (Padulosi et al., 2019; Heindorf et al., 2021). NUS can be found across various agroclimatic regions and landscapes suitable for agriculture. For example, 77 NUS in the form of leafy vegetables, tuber, edible wild fruits, and legumes have been found in Vietnam highlands (Vu and Nguyen, 2017).

Research into NUS has gained momentum over the years, with a focus on diversifying food crops to fight hunger and provide agricultural resilience (Li and Siddique, 2020; Mustafa et al., 2021; Siddique et al., 2021), and some could be mainstreamed into the food system, particularly those rich in protein and minerals or medicinal properties (Mudau et al., 2022). Bambara groundnut (*Vigna subterranea*) (Mayes et al., 2019; Tan et al., 2020), winged bean (*Psophocarpus tetragonolobus*) (Adegboyega et al., 2019; Tanzi et al., 2019) and amaranth (*Amaranthus* spp.) (Sarker et al., 2020; Jamalluddin et al., 2021) have high fiber content and nutrients, such as protein, carbohydrates, unsaturated fatty acids, and essential minerals. They are thus good candidates to supplement food systems to overcome malnourishment in adults and children (Talabi et al., 2022). Breeding programs have been developed to produce improved varieties of NUS crop species by initially characterizing germplasm. The African Orphan Crops Consortium (AOCC), in global partnership with biotechnology industries and research institutions, has initiated plans to assemble the genome sequence of 101 traditional African food crops for genetic improvement (Jamnadass et al., 2020; African Orphan Crops Consortium, 2022). To date, the genomes of at least 29 orphan crops in nine families have been sequenced, including Fonio (*Digitaria exilis*) (Abrouk et al., 2020), African eggplant (*Solanum aethiopicum*), breadfruit (*Artocarpus altilis*), apple-ring acacia (*Faidherbia albida*), Bambara groundnut (*Vigna subterranea*), jackfruit (*Artocarpus heterophyllus*), lablab (*Lablab purpureus*), marula (*Sclerocarya birrea*) and moringa (*Moringa oleifera*) (Chapman et al., 2022).

Indigenous fruit tree species (IFTs), which also falls under underutilized food crop, should be given equal emphasis as candidates for crop diversification. Tree commodities play a crucial role in diversifying crop production through agroforestry practices, which contribute to sustainable development goals in Africa (Mbow et al., 2014; Minang et al., 2021). Domesticated IFTs have two main benefits, the first being naturally nitrogen-fixing tree

species such as leguminous type can help restore the land and improve soil nutrient availability. Second, fruit trees offer nutritious foods, with a surplus, can also be turned into a source of income for farmers from fruit selling, on top of fuel wood and timber trades (Leakey, 2014, 2020). Both benefits of agroforestry practices have translated into overall farmers' wellbeing, as shown from interviews and discussions with subsistence farmers in western Kenya (Thorlakson and Neufeldt, 2012). IFTs are valuable for their edible fruits/nuts and most of their plant parts. For example, *Garcinia livingstonei* (African mangosteen)'s stem bark has a skin lightening effect on human skin (Mulholland et al., 2013), and its fruit contains high levels of macro and micro elements (Joseph et al., 2017). At least 29 IFT species within the South African provinces have been identified as potentials for commercialization (Nkosi et al., 2020). Domesticating IFTs through species diversity characterization could potentially close the yield gap, thereby increasing the harvest yield (Suliman and Mariod, 2019).

Crop wild relatives and their associated weedy forms of agricultural crops are great genetic resources for trait improvement in cultivated species, including tolerance to a range of abiotic and biotic stresses, with many carrying out the C4 photosynthesis and thus adaptable to warm and dry environmental conditions (Ye and Fan, 2021). With good breeding models, prediction tools for the optimal selection of useful alleles and their introgression into elite pools with minimal linkage drag are possible (Cowling, 2013; Cowling et al., 2017). An initiative to collect wild, weedy, or landrace materials representing 29 target crops sourced from their country of origin and other exotic places was carried out by the Crop Trust Crop Wild Relatives Project, with expertise from 170 worldwide research institutes and breeding programs in 70 countries to conserve valuable wild germplasm in *ex-situ* collections, for plant breeders, researchers and farmers (Khoury et al., 2010; Crop Trust Annual Report 2021, 2022). Output from the project includes the collection of eggplant *Solanum* genus wild relatives from partners in 12 countries, 17 samples of wild Bambara groundnut from Nigeria not found in genebanks previously, and pre-breeding lines derived from crop wild relatives and landraces of grasspea and finger millet, with more than 14,000 pre-bred lines from 19 crops available to crop researchers and farmers (Crop Trust, 2019; Crop Trust Annual Report 2021, 2022).

6.4. Technology diversification

Advances in agricultural practices and plant breeding methods are key to securing food for the future. Collaborative networks between farmers, private and government research institutions, agronomists, researchers, and industry professionals in breeding programs drive knowledge and technology transfer through active dialogues and participatory research. Such an example includes the sorghum network in Mali involving ICRISAT and farmer organizations to strengthen the seed system (Rattunde et al., 2021). Supported by reliable international, regional, or local agricultural research funding bodies and expertise, integrating farmers' indigenous in-farm knowledge with modern scientific knowledge in plant breeding will stimulate innovation and real-life application to boost sustainable agriculture productivity (Dawoe

et al., 2012; Pagliarino et al., 2020). Farmer field school offers an experiential learning approach where a group of farmers works together with the facilitator, discussing regularly the various situations encountered in the field and coming up with solutions of empowering farmers' capability in agrosystem management and expand their knowledge base (Bakker et al., 2021, 2022).

Cutting-edge biotechnology tools, such as genome sequencing, pangenomics, SNP marker discovery, and genotyping, genome-wide association studies, and genomic selection approaches, have revolutionized crop breeding with smarter and more targeted ways to improve crop productivity (Bayer et al., 2021; Marsh et al., 2021), as seen by the advances in many major crop species and application in NUS crops (Tay Fernandez et al., 2022). These tools will benefit crop breeding, provided sufficient plant material is available that covers a wide genetic diversity for each crop species (major and NUS) (Khan et al., 2020; Mohd Saad et al., 2021).

Viable plant materials from the world's food crops are well conserved in genebanks worldwide. Online resources such as Genesys, containing the genebank database, make it convenient for researchers to perform research and studies (Genesys, 2022). For example, the current wheat germplasm collection contains more than 800,000 accessions held in 80 different collections, with CIMMYT hosting the largest wheat collection worldwide (Crop Wild Relative Diversity, 2022). This large pool of genetic resources, with as many as 80,000 wheat accessions sourced from tetraploid species, wild relatives, and landraces, has been studied for its genetic diversity using DArTseq and SilicoDArT approaches (Sansaloni et al., 2020). The global genetic yield gap for wheat is estimated at 51% due to suboptimal crop and soil management, indicating that there is room to improve crop productivity through genetic improvements by tapping into the large wheat germplasm resources (Senapati et al., 2022). Another example is the genotyping of the entire collection of barley accessions from the German *ex-situ* collection, with 22,626 accessions, using genotyping-by-sequencing to differentiate and track redundant material in the genebank (Milner et al., 2019). Combining high-throughput genotyping with high-throughput phenotyping (Danilevich et al., 2021) using machine learning (Khotimah et al., 2020) makes it possible to accurately identify the diversity underlying agronomic traits.

Maize, wheat, and soybean productivity can be improved to reduce import requirements by combining various modern breeding techniques, such as genomics-assisted breeding, phenomics, artificial intelligence, and gene editing (Naqvi et al., 2022), to overcome the limitations of climate-dependent food crops by developing tropical varieties. Besides, investing in the latest breeding technologies would facilitate knowledge transfer from lab to the field, potentially improving crop productivity. For example, Japan, Korea, and China are the origin sites of domestication for soybean; on-site plant materials collection and data analysis supported by genomics facilities means cost-saving in terms of time and resources at the same time, translating research outputs into improving soybean production in their own countries (Li et al., 2020). The International Maize and Wheat Improvement Center (CIMMYT) developed maize hybrids acclimated to South and South East Asia climate zones (CIMMYT, 2019).

Crop pangenomics resources are useful for plant breeding and improvement, revealing valuable information for breeders to tap into from the large diversity of a species (Golicz et al., 2016; Bayer

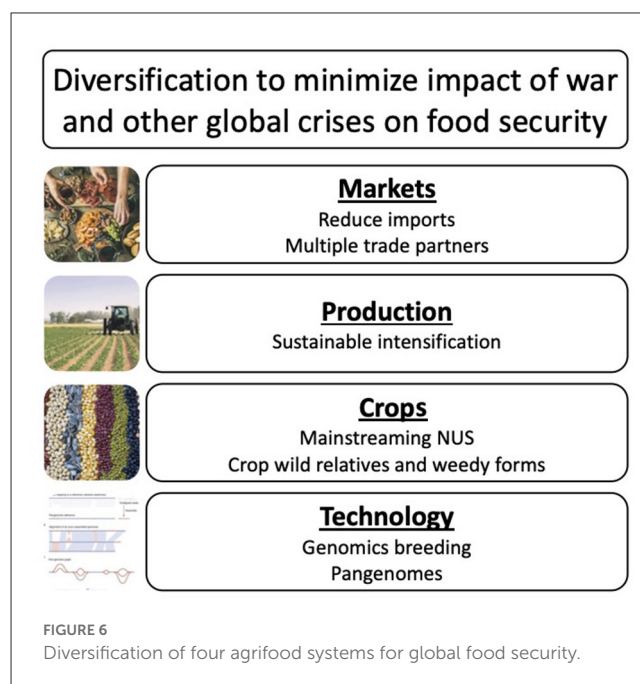
et al., 2020, 2022a; Zanini et al., 2022). For example, the soybean pangenome from the USDA collection revealed more genes with lower frequencies, such as those controlling plant architecture and seed composition, than those with higher frequencies, such as those controlling flowering time and stress tolerance traits; this gives breeders an idea of which genes to select from which accession during the selective breeding process (“smart” breeding) (Bayer et al., 2022b). In addition to genomes and pangenomes being developed for major crops, they are also being constructed for crops important in developing countries, such as banana (Rijzaani et al., 2022), yam bean (Tay Fernandez et al., 2021), sorghum (Ruperao et al., 2021), chickpea (Varshney et al., 2013) and pigeonpea (Zhao et al., 2020). Ongoing efforts have been made to build pangenomics resources for developing climate-ready crops (Marsh et al., 2021; Petereit et al., 2022).

Crop mutation breeding, a plant breeding technique that uses induced mutation in plants for better adaptability to the environment, generates genetic variation for crop improvement (Forster and Shu, 2012). The Plant Mutation Breeding Network for Asia and the Pacific established by the Joint FAO/IAEA Center successfully released improved varieties of cowpea in Zimbabwe using the irradiation method, with improved drought tolerance and insect resistance and increasing yields by 10–20% (Dixit and Slavchev, 2018). With the development of genome editing techniques, it is possible to generate precise modifications in genomes. When this technology is combined with the knowledge of pangenomes and associated traits, it is possible to accelerate the production of climate-ready crops to support future food security (Mohd Saad et al., 2021; Varshney et al., 2021a,b; Derbyshire et al., 2022).

In summary, by considering the diversification in four aspects of agrifood systems, we believe the goal of attaining a more sustainable, shock-resilient, and improved global food security is not far-reaching (Figure 6).

7. Future perspectives and conclusion

The Russia–Ukraine conflict has highlighted the vulnerability of global food security and underscored the critical need to achieve food resilience by transforming and diversifying agrifood systems. We propose diversification in food markets, production, crop, and technology to secure global food supply and build resilience toward future shocks. Specifically, there should be stronger support for increasing market demand for alternative foods. It is important to consider sustainable intensification in producing sufficient food to feed the growing global population with minimal risks to the natural ecosystems. Concerted efforts at the global, regional, national, and local levels are needed to fulfill the mandate of global food security through policymaking, increased consumer awareness, knowledge of food markets, adding value with NUS crops, and research investments using advanced biotechnology tools to enhance crop productivity. At the smallholder farmers’ level, the efficiency and productivity of production and processing markets for food crops, including indigenous fruit trees, could be improved by creating platforms for farmers to distribute their fresh harvest directly to consumers. Food system experts indicate that food resilience research should focus



on prediction tools and high-quality, local-scale on-the-ground data collection to determine the impact of extreme events on food security (Mehrabi et al., 2022). Within the context of long-term food crop trials, practical implementation *via* participatory on-farm research using real-time farming challenges could provide solutions for NGOs, consumers, academia, policymakers, and value chain experts (Riar and Bhullar, 2020). Incorporating all these roles, carried out by diverse players in the agri-food industry, should combat hunger by 2030 and fight the global food crisis.

Author contributions

TN and FM conceptualized the study. TN wrote the first draft of the manuscript. BKS wrote sections of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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