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Agriculture, food security, and sustainability: a review

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Abstract

Agriculture is pivotal in securing global food security and sustainability, especially in pressing challenges such as climate change, population growth, and resource depletion. This review examines the interconnections between agriculture, food security, and sustainability, focusing on current challenges, innovations, and strategies to address these critical issues. The global demand for food is projected to increase substantially, necessitating agricultural systems that boost productivity and ensure environmental sustainability. However, conventional farming practices have exacerbated soil degradation, water scarcity, and greenhouse gas emissions, posing significant threats to long-term food security. This review aims to evaluate the role of sustainable agricultural practices in enhancing food security while mitigating environmental impacts. It also identifies existing gaps in farming systems and explores innovative solutions to promote resilient and sustainable food systems. A comprehensive review of peer-reviewed literature, policy documents, and global agricultural reports was conducted. The analysis focuses on key themes such as sustainable farming practices, the impacts of climate change on agriculture, advancements in agrotechnology, and the socio-economic dimensions of food security. Synthesized findings provide actionable insights into best practices and emerging trends. Sustainable agriculture offers a viable pathway to address the dual challenges of food security and environmental conservation. Precision farming, agroecology, and regenerative agriculture enhance productivity while preserving resources and reducing ecological footprints. Integrating advanced technologies, including artificial intelligence and genetic innovations, can optimize agricultural efficiency. However, global food security requires coordinated efforts among governments, the private sector, and local communities to implement equitable resource distribution and climate-resilient policies. Future research should prioritize scalable, region-specific solutions that align with sustainability principles to ensure a secure and resilient global food system.

Keywords

Agriculture, food security, farm productivity, innovative strategies, global food

Introduction

Agriculture has been a cornerstone of human civilization, providing the essential food, fiber, and resources for survival, economic development, and societal advancement. As the global population is projected to reach nearly 10 billion by 2050, ensuring food security—the availability, accessibility, utilization, and stability of the food supply, has become one of the most pressing challenges of our time [1]. The intricate relationship between agriculture and food security underscores the importance of sustainable agricultural practices that enhance productivity, conserve natural resources, and protect ecosystems. However, modern agriculture faces multifaceted challenges, including climate change, land degradation, water scarcity, and socioeconomic inequalities, which collectively threaten its ability to meet the growing global demand for food [2].

This review explores the complex interplay between agriculture, food security, and sustainability, emphasizing the urgent need for transformative solutions that address these challenges while promoting environmental stewardship and equitable resource distribution [3]. Specifically, this paper highlights innovative strategies such as climate-smart agriculture (CSA), developing resilient crop varieties, efficient water management systems, and integrating digital technologies to optimize agricultural systems. It also examines the socioeconomic dimensions of food security, including access, equity, and the role of global trade policies in fostering fair and stable food markets. Addressing these challenges requires transformative solutions such as CSA practices, advancements in crop genetics, and efficient water management strategies to meet the growing food demand without undermining the capacity of future generations to produce food [4]. Additionally, achieving food security necessitates a broader focus beyond production, addressing systemic issues of distribution, equity, and accessibility, as millions remain malnourished despite global food surpluses [5]. These efforts align with the United Nations Sustainable Development Goal (SDG) of ending hunger and ensuring universal access to safe, nutritious, and sufficient food by 2030 [6, 7].

Agricultural regulations play a vital role in global food security by addressing the availability, accessibility, stability, and utilization of food [8, 9]. These regulations establish policy frameworks that guide sustainable production, distribution, and consumption practices while safeguarding public health and environmental resources [10, 11]. The primary focus of these regulations is food safety, a critical component of food security. Standards established by organizations such as the United States Food and Drug Administration (FDA) [12] and the European Food Safety Authority (EFSA) regulate pesticide residues, contaminants, and foodborne pathogens [13]. These standards ensure rigorous testing and certification processes to eliminate unsafe foods from supply chains [14, 15]. Maintaining high food safety standards fosters consumer trust, essential for domestic and international food markets [16]. Environmental sustainability, another key regulatory focus, directly influences global food security. Unsustainable agricultural practices contribute to soil degradation, water scarcity, and biodiversity loss, compromising long-term productivity [17]. Regulatory frameworks such as the European Union's Common Agricultural Policy (CAP) and the United States Environmental Protection Agency (EPA) guidelines incentivize practices that conserve natural resources, reduce greenhouse gas emissions, and enhance ecosystem health [18, 19]. These measures promote the resilience of food production systems to climate change and other environmental stresses. Labor regulations within agriculture also play a critical role in ensuring food security. Policies that enforce fair wages, safe working conditions, and protections against child labor contribute to a stable and motivated agricultural workforce [20, 21]. A well-protected workforce enhances productivity, ensuring efficient and sustainable food production systems.

In the mid-20th century, India faced severe food shortages and depended highly on imports. The Green Revolution (1960–1970s) introduced high-yielding variety (HYV) seeds, improved irrigation infrastructure, and chemical fertilizers. This transformation led to significant increases in wheat and rice production, making India self-sufficient in food grains. By 1978, wheat production increased from 12 million tons (1965) to over 36 million tons [22]. However, the Green Revolution also had environmental consequences, such as soil degradation and groundwater depletion, and challenging long-term sustainability. This case illustrates how agricultural advancements can boost food security but must be balanced with sustainability considerations. Ethiopia experienced one of the deadliest famines (1983–1985) in history, caused by prolonged drought and political instability. Agriculture in Ethiopia was heavily rain-fed, leaving it highly vulnerable to climate variability. Crop failures and livestock losses led to widespread hunger, with over 400,000 deaths [23]. This tragedy underscored the importance of building climate-resilient agricultural systems, such as irrigation, drought-resistant crops, and early warning systems, to safeguard food security. The case highlights how agriculture's vulnerability to environmental factors directly affects food security in climate-sensitive regions. Despite its limited land area, the Netherlands has become a global leader in agricultural exports through precision farming technologies. Innovations such as greenhouse farming, automated irrigation, and data-driven crop management have enabled farmers to maximize yields while minimizing resource use. For example, Dutch farmers use 90% less water for growing vegetables than global averages [24]. This case demonstrates how technology-driven agricultural systems can enhance productivity and sustainability, contributing to food security globally.

Sub-Saharan Africa highly depends on agriculture, which employs nearly 60% of the population. However, climate change has exacerbated droughts, reduced rainfall, and increased temperatures, negatively impacting staple crops such as maize, millet, and sorghum. Studies estimate that cereal yields could decline by up to 20% by 2050 without adaptation measures [25]. CSA practices, including agroforestry and drought-tolerant crops, are being promoted to build resilience. This case underscores the need to adapt farming systems to climate change to ensure food security for vulnerable populations. The COVID-19 pandemic disrupted global agricultural supply chains, affecting food production, processing, and distribution. Lockdowns and labor shortages hindered agrarian activities, while transport restrictions delayed the movement of perishable goods. In 2020, global food insecurity rose sharply, with an additional 161 million people experiencing hunger [26]. Localized food production and supply chain diversification are emerging as key strategies to enhance resilience. This case highlights the interdependence between robust agricultural systems and food security, especially during global crises.

Trade policies significantly impact food security by governing the international flow of agricultural products. Tariffs, subsidies, and trade agreements regulated by entities such as the World Trade Organization (WTO) aim to create fair and stable markets, mitigating local food shortages through global food distribution [27]. These policies support equitable trade practices, benefiting farmers in developing countries while ensuring fair compensation and fostering local agricultural development. International collaboration is vital to harmonizing farm regulations and addressing transboundary challenges. Initiatives such as the Codex Alimentarius, established by the Food and Agriculture Organization (FAO) and World Health Organization (WHO), provide globally recognized food safety and quality standards. Such cooperation is essential for managing cross-border issues threatening global food supplies, including plant and animal diseases [28, 29].

Despite progress, significant challenges persist. Climate change remains a substantial threat to food security, with extreme weather events disrupting agricultural productivity and supply chains [19, 30, 31]. Regulatory frameworks must evolve to promote climate-resilient farming practices and adaptive management strategies. The growing global population and shifting dietary preferences also pressure agricultural systems, necessitating continuous innovation and policy advancements. Technological developments, such as biotechnology and digital agriculture, offer promising solutions and introduce regulatory complexities. Genetically modified organisms (GMOs) and precision farming technologies can enhance productivity and resource efficiency [32]. However, their adoption requires robust regulatory mechanisms to address safety concerns and public perceptions. Bridging the regulatory gaps between developed and developing nations is equally crucial. Capacity-building initiatives, including technical training and financial support, can empower developing countries to implement and enforce effective regulations, contributing to global food security [33].

Furthermore, this review aims to align its discussion with the United Nations' SDGs, particularly goal 2, which seeks to end hunger and ensure access to safe, nutritious, and sufficient food for all by 2030. This study aims to provide actionable insights for policymakers, researchers, and stakeholders to collaboratively build resilient, inclusive, and sustainable food systems by analyzing current trends, challenges, and opportunities. Ultimately, achieving the dual goals of food security and environmental sustainability will require innovative policies, international cooperation, and the mobilization of scientific advancements to transform agriculture into a sustainable foundation for feeding the world's growing population.

The role of agriculture in food production

Agriculture is the foundation of the global food system. It is responsible for producing most of the food consumed by humans, including staple crops such as rice, wheat, and maize, as well as fruits, vegetables, and livestock products. According to FAO, agriculture employs more than one billion people worldwide, making it the largest employer globally [34]. In addition to its economic importance, agriculture is deeply intertwined with many regions' cultural practices, traditions, and social structures. However, the capacity of agriculture to meet the growing demand for food is increasingly under strain. The world's population is expected to reach nearly 10 billion by 2050, which will require a 50% increase in food production compared to current levels [35, 36]. This demand growth occurs in the context of significant environmental and socio-economic challenges, such as climate change, soil degradation, water scarcity, and unequal access to resources. These challenges threaten the sustainability of agricultural systems and, by extension, global food security. The key aspects of agriculture and global food security are presented in Figure 1 [26, 27, 37–39].

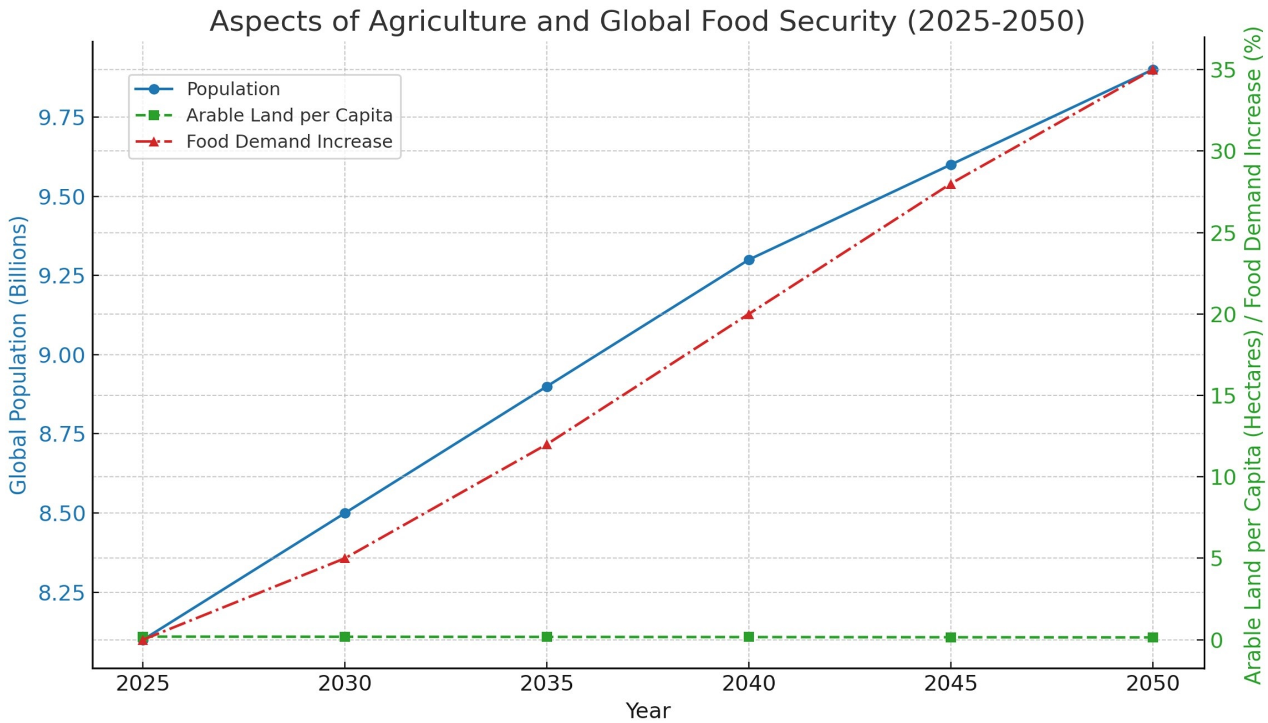

Figure 1. The critical aspects of global food security between 2020–2050

Food security

Food security is a multi-dimensional concept encompassing availability, access, utilization, and stability [9, 40, 41]. The FAO defines food security as a situation where "all people, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food that meets their dietary needs and food preferences for an active and healthy life" [42, 43]. This definition highlights the complex and interconnected factors influencing food security, including agricultural productivity, economic policies, social equity, and environmental sustainability. The four pillars of food security, availability, access, utilization, and stability are critical for understanding the challenges of feeding a growing global population. (i) Availability refers to the physical food supply, which is determined by agricultural production, stock levels, and net trade. (ii) Access involves the ability of individuals to obtain food, which is influenced by factors such as income levels, food prices, and distribution systems. (iii) Utilization relates to food's nutritional quality and safety and individuals' ability to absorb nutrients, which affect health status and sanitation. (iv) Stability concerns the reliability of food supplies over time, which can be disrupted by economic shocks, political instability, or environmental disasters [44]. Figure 2 shows the agriculture and food security challenges, strategies, and outcomes.

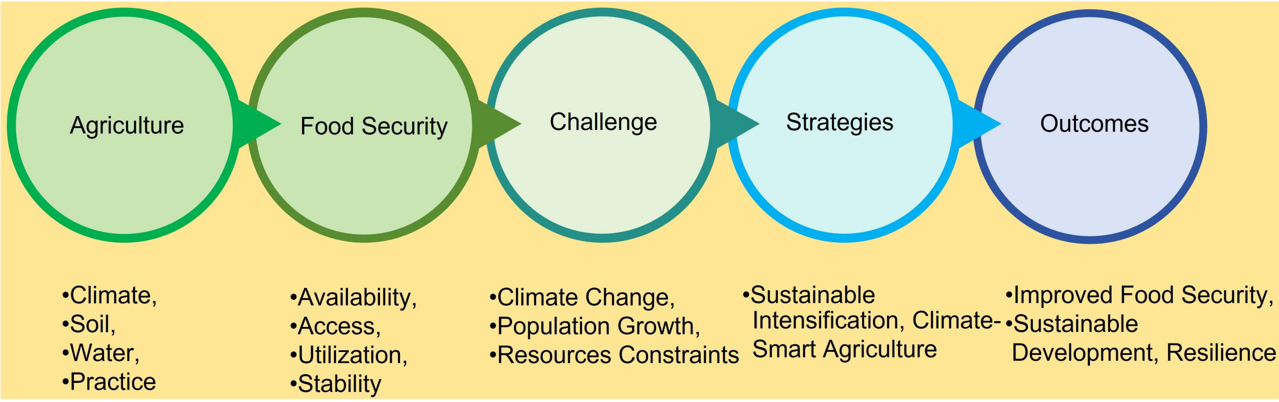

Figure 2. Agriculture, food security, sustainability challenges, strategies, and outcomes

Challenges facing agriculture and food security

The interdependence between agriculture and food security is evident: Sustainable agricultural practices are essential to maintaining food supply chains and ensuring that future generations have access to adequate nutrition (Figure 2). However, various factors increasingly challenge agriculture's ability to fulfill this role.

Climate change

Climate change is one of the most significant threats to global food security and sustainability in the 21st century [45–47]. As global temperatures rise, weather patterns shift, and extreme climate events become more frequent, the intricate balance of agricultural systems is increasingly disrupted, with profound implications for global food systems and environmental sustainability. Climate changes, precipitation patterns, and the frequency of extreme weather events, such as droughts and floods, directly affect crop yields and livestock productivity. For example, studies have shown that a 2°C increase in global temperatures could reduce the yields of major crops like wheat, rice, and maize by up to 25% in some regions [42, 47, 48]. Additionally, rising sea levels and increased salinization of coastal soils pose risks to agricultural lands, particularly in low-lying areas [49]. Agriculture is susceptible to climate variations. Rising temperatures and changes in precipitation patterns directly affect crop yields, livestock health, and soil fertility. Prolonged droughts, intense heatwaves, and flooding can reduce agricultural productivity by damaging crops, disrupting planting schedules, and increasing pest and disease outbreaks. For example, staple crops like wheat, rice, and maize, the backbone of the global food supply, are particularly vulnerable to heat stress, leading to reduced yields and increased production costs. Furthermore, shifting climate zones force farmers to adapt by altering cropping patterns or relocating agricultural activities, which may not always be feasible. Climate change exacerbates food insecurity by disrupting the availability, accessibility, and affordability of food. Reduced crop yields and livestock productivity increase food prices, disproportionately affecting low-income populations [50]. Extreme weather events like hurricanes and floods further strain food supply chains by damaging infrastructure and disrupting transportation networks. Regions already grappling with food insecurity, such as sub-Saharan Africa and South Asia, are particularly vulnerable to these effects. In addition, climate-induced displacement of communities can lead to increased competition for resources, further exacerbating food scarcity in affected regions [51].

Sustainability in agriculture hinges on the efficient use of natural resources, environmental stewardship, and resilience to external shocks. Climate change undermines these principles by accelerating soil degradation, depleting water resources, and threatening biodiversity. For instance, erratic rainfall patterns and prolonged droughts deplete freshwater supplies, intensifying competition for water between agricultural, industrial, and domestic uses [52]. Similarly, the loss of biodiversity due to habitat destruction and changing ecosystems weakens natural processes, such as pollination and pest control, which are critical for sustainable farming systems. Mitigating the impact of climate change on agriculture, food security, and sustainability requires a multi-faceted approach [53], such as:

- CSA: practices that boost resilience, such as agroforestry, conservation agriculture, and precision farming, can facilitate farmers' adaptation to changing environments while lowering greenhouse gas emissions.
- Financing in research and innovation: it is critical to foster climate-resilient crop varieties, enhance irrigation competence, and innovate digital technologies for climate observing and early alert systems.
- Policy reinforce: governments and international concerns must spotlight policies that advance sustainable land and water control, incentivize renewable energy use in agriculture, and provide economic and technological cooperation to farmers.
- Global alliance: directing climate change's effect on agriculture expects shared action, including international agreements, knowledge sharing, and financing for adjustment and mitigation proposals in exposed regions.

Climate change, food security, and sustainability confront the challenge of urgent and groundbreaking resolutions. By selecting resilience, sustainability, and equity in agricultural approaches, humankind can safeguard food security for forthcoming generations while dismissing agriculture's ecological trajectory. Directing on climate change in agriculture is an obligation for persistence and an opening to generate a more sustainable and rightful global food system.

Soil degradation and water scarcity

Soil degradation, including erosion, nutrient depletion, and loss of organic matter, is a significant concern for global agriculture. Approximately 33% of the world's arable land has been lost to erosion or pollution over the last 40 years [54]. This loss of productive land undermines agricultural capacity and exacerbates food insecurity, particularly in regions already facing resource constraints. Water scarcity is another critical issue, with agriculture accounting for approximately 70% of global freshwater withdrawals [55]. The increasing competition for water resources, driven by population growth, urbanization, and industrialization, puts pressure on water availability for agriculture. In many regions, the over-extraction of groundwater and the depletion of rivers and lakes leads to the unsustainable use of water resources, threatening the long-term viability of agricultural systems [47, 56, 57].

Loss of biodiversity

Biodiversity loss is a significant threat to the resilience of agricultural systems [58]. The genetic diversity of crops and livestock is essential for breeding new varieties resistant to pests, diseases, and environmental stresses. However, modern farming practices, such as monocropping and the widespread use of chemical inputs, have reduced farm biodiversity [1]. The loss of biodiversity reduces agriculture's ability to adapt to changing conditions and undermines ecosystem services, such as pollination and soil fertility, which are critical for food production.

Socio-economic inequality

Socio-economic inequality is a significant barrier to food security, particularly in developing countries. Despite the global abundance of food, nearly 690 million people worldwide were undernourished in 2019, a rise from 2014 [39, 43, 59]. Inequities in income, access to resources, and political power often result in unequal access to food, with vulnerable populations, such as smallholder farmers, women, and children, being disproportionately affected.

Strategies for enhancing food security through sustainable agriculture

Addressing agriculture and food security challenges requires a holistic and integrated approach. Sustainable agricultural practices, which seek to balance productivity with environmental stewardship and social equity, offer a pathway to achieving food security in the face of these challenges. There are several key strategies.

Promoting CSA

CSA involves practices that increase productivity while enhancing resilience to climate change and reducing greenhouse gas emissions [60, 61]. Techniques such as conservation agriculture, agroforestry, and integrated pest management (IPM) can help farmers adapt to changing conditions and reduce the environmental impact of agriculture [62, 63]. Improving the efficiency of resource use, particularly water and soil, is critical for sustainable agriculture [64]. Drip irrigation, rainwater harvesting, and precision agriculture can reduce water use and improve crop yields. Similarly, crop rotation, cover cropping, and organic farming can enhance soil health and reduce the need for chemical inputs [19, 65].

Protecting and enhancing biodiversity

Maintaining and enhancing agricultural biodiversity is essential for the long-term sustainability of food systems. This includes preserving traditional crop varieties, promoting diverse cropping systems, and protecting natural habitats that support beneficial species such as pollinators [58]. Conservation efforts at the genetic, species, and ecosystem levels are necessary to ensure the resilience of agricultural systems [66].

Addressing inequality and empowering communities

Socio-economic inequality is crucial for achieving food security [67, 68]. This involves ensuring that smallholder farmers, women, and marginalized groups have access to resources, markets, and decision-making processes. Empowering communities through education, capacity building, and equitable policies can help create more inclusive and resilient food systems [69, 70]. Figure 3 shows a stepwise outline of agriculture's main components and relationships with food security.

The role of agriculture in global food security

Agriculture is the primary source of food production, making it a cornerstone of food security. It encompasses the cultivation of crops, rearing of livestock, forestry, and fisheries. The sector ensures the availability of diverse and nutritious foods crucial for a healthy population. In many developing countries, agriculture is the primary source of income and employment, directly impacting the food security of millions. The relationship between global food security and agricultural policies is shown in Table 1.

Several factors influence the ability of agriculture to sustain food security.

Agricultural productivity and climate change

The productivity of farming systems is vital for ensuring a stable food supply [45, 86]. Advances in agricultural technologies, including high-yielding crop varieties, precision farming, and sustainable practices, have significantly enhanced food production [87]. For instance, the Green Revolution in the mid-20th century led to remarkable increases in food production in Asia and Latin America, improving food security in these regions. Climate change poses a significant threat to agriculture and, consequently, to food security. Extreme weather events, shifting weather patterns, and the increasing frequency of droughts and floods can devastate crops and reduce agricultural productivity [63, 88]. According to the FAO, climate change could reduce agricultural yields by up to 25% by 2050, with the most severe impacts expected in developing countries where food insecurity is already prevalent [61, 89]. The availability and management

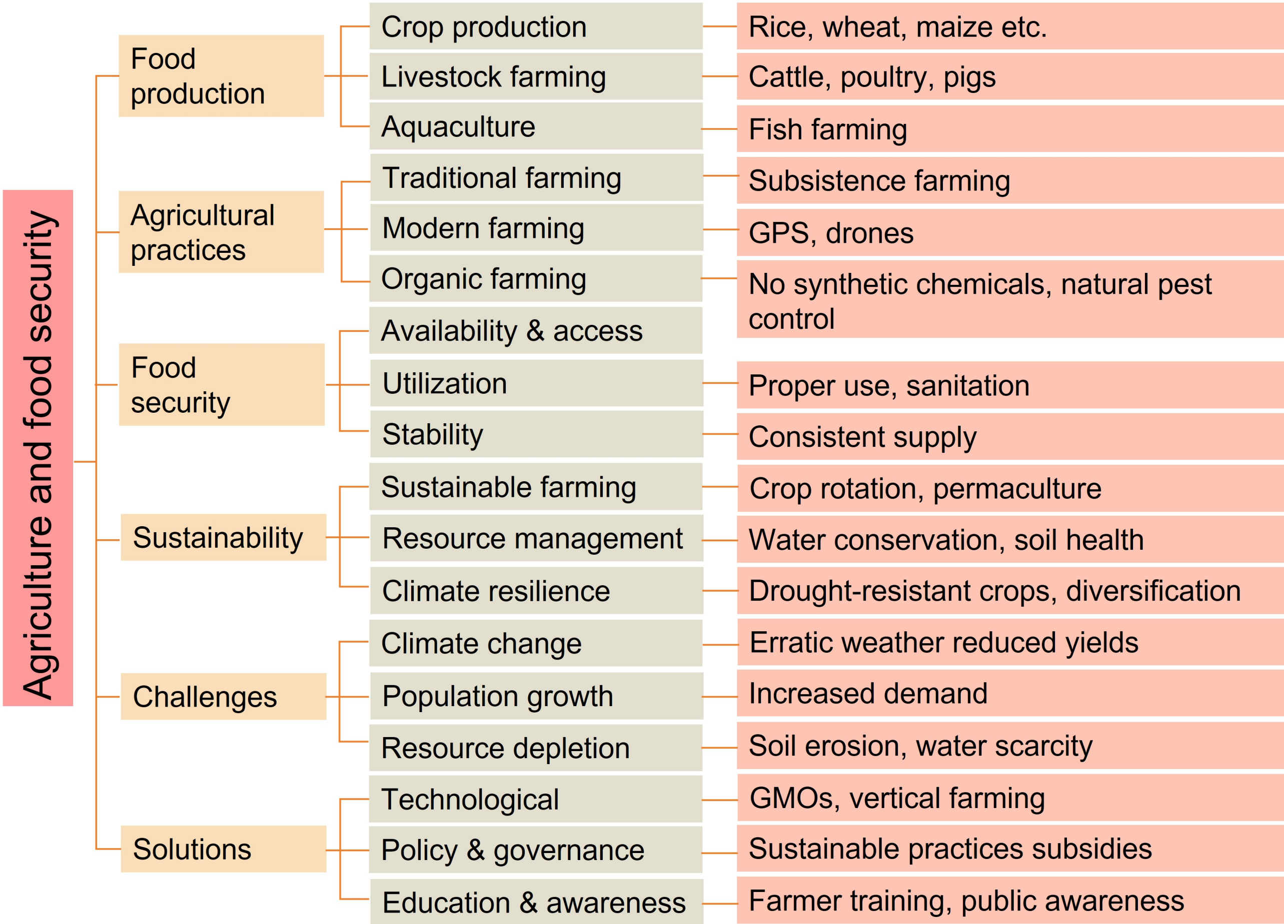

Figure 3. Outline of agriculture's main components and relationships with food security. GMOs: genetically modified organisms; GPS: global positioning system

Table 1. Global food security with agricultural policies

The aspect of food security	Agricultural policies	Examples
Food safety	Regulations ensure food products are free from harmful contaminants, pesticides, and pathogens.	Food and Drug Administration (FDA), European Food Safety Authority (EFSA) [13, 71]
Environmental sustainability	Laws and policies promote sustainable farming practices to protect soil, water, and biodiversity.	European Union (EU), Environmental Protection Agency (EPA) [72, 73]
Labor conditions	Protocols ensure fair wages and safe working conditions and prohibit child labor.	International Labor Organization (ILO), Fair Labor Standards Act (FLSA) [20, 74–76]
Trade policies	Policies govern the import and export of agricultural products, affecting global food availability and prices.	World Trade Organization (WTO), United States Department of Agriculture (USDA) [28, 77, 78]
International cooperation	Global standards and guidelines harmonize regulations to address food security challenges collaboratively.	Food and Agriculture Organization (FAO)/World Health Organization (WHO), United Nations Framework Convention on Climate Change (UNFCCC) [30, 79]
Climate change adaptation	Guidelines promote climate-resilient agricultural practices to mitigate the impacts of extreme weather.	Government of Australia (GA), EU [80–82]
Technological integration	Organizing overseas the safe integration of biotechnology and digital agriculture innovations.	Genetically modified organisms (GMOs) (USDA), EU [81–83]
Capacity building	International aid and training programs enhance regulatory capabilities in developing countries.	FAO, United States Agency for International Development (USAID) [78, 84, 85]

of natural resources, particularly land and water, are critical for agricultural productivity [65, 90]. Soil degradation, deforestation, and water scarcity are significant challenges that threaten the sustainability of agriculture. Efficient use of these resources through crop rotation, agroforestry, and irrigation management can enhance food security by ensuring long-term agricultural productivity [64, 90, 91].

Economic factors, social, and political stability

Market access, pricing policies, and trade regulations significantly influence agriculture's role in food security. Farmers need access to markets to sell their produce reasonably, and consumers need affordable and nutritious food. Economic policies that support smallholder farmers in reducing food waste and promoting fair trade can enhance food security [92, 93]. Food security also depends on social and political factors. Conflict, instability, and poor governance can disrupt agricultural production and distribution, leading to food shortages and famine [67]. Ensuring political stability and good governance is essential for creating an environment where agriculture can thrive and contribute to food security.

Challenges to agriculture and global food security

The above table also summarizes how agricultural regulations contribute to ensuring global food security by addressing critical areas, from food safety and environmental sustainability to labor conditions and international trade policies. Despite the crucial role of agriculture in ensuring food security, several challenges hinder its effectiveness.

Population growth and environmental degradation

The global population is projected to reach 9.7 billion by 2050, increasing the demand for food by 70%. Meeting this demand will require a significant increase in agricultural productivity, which is challenging given the constraints on natural resources and the impacts of climate change [45, 94, 95]. As mentioned earlier, climate change and environmental degradation threaten agricultural productivity. The increasing frequency of extreme weather events, rising temperatures, and changing precipitation patterns can reduce crop yields and affect food quality [45, 47, 63, 96]. Rapid urbanization is reducing the amount of arable land available for agriculture, particularly in developing countries. Urban expansion often converts fertile agricultural land into metropolitan areas, reducing the land available for food production [9, 97, 98]. Approximately one-third of all food produced globally is wasted, representing a significant loss of resources and contributing to food insecurity. Reducing food waste through improved storage, transportation, and consumption practices is essential for enhancing food security [99, 100].

Pests and diseases

Agricultural production is vulnerable to pests and diseases, which can lead to significant crop losses. Climate change and global trade exacerbate the spread of pests and diseases, making it a growing concern for food security [101, 102].

Strategies to enhance agriculture and global food security

To overcome these challenges and ensure that agriculture continues to contribute to food security, several strategies can be implemented.

Sustainable agricultural practices

Promoting sustainable agricultural practices is essential for enhancing food security. Crop diversification, conservation agriculture, IPM, and organic farming can improve agricultural productivity while preserving natural resources [65, 87, 103]. Continued farm research and development investment is crucial for developing new technologies and practices to enhance agricultural productivity. Research on drought-resistant crops, precision farming, and biotechnology can help farmers adapt to changing environmental conditions and improve food security [68, 95, 104–106].

Strengthening rural infrastructure and CSA

Improving rural infrastructure, including roads, storage facilities, and irrigation systems, can enhance agricultural productivity and reduce post-harvest losses. Access to reliable infrastructure also improves farmers' access to markets, enabling them to sell their produce at fair prices [41, 107]. Smallholder farmers are critical in food production, particularly in developing countries. Empowering these farmers through access to credit, extension services, and market information can enhance their productivity and contribute to food security [67, 108]. Governments and international organizations must implement policies supporting agricultural development and food security. These policies should include measures to support sustainable agriculture, reduce food waste, and ensure fair trade practices [40, 97]. Adopting CSA practices can help mitigate the impacts of climate change on agriculture. These practices include using drought-resistant crop varieties, improving water management, and enhancing soil fertility through sustainable land management practices [107, 109].

Risks to agriculture and food security from major disruptions

Severe global events, such as large-scale volcanic eruptions and nuclear wars, threaten food security by interrupting agricultural systems and supply chains [89]. The critical link between agricultural policy and global food security is shown in Table 2. Volcanic eruptions, such as the 1815 eruption of Mount Tambora, have historically caused "volcanic winters" where ash clouds block sunlight, reducing global temperatures and impairing crop yields [89, 110]. These climatic interferences can result in extensive famine, as demonstrated by the year without a summer in 1816, which led to agricultural collapse in Europe and North America [111]. Similarly, the aftermath of a nuclear war—often called 'nuclear winter' would affect noteworthy atmospheric soot and aerosols, significantly reducing sunlight and dropping temperatures worldwide [112–114]. This situation would relentlessly impede photosynthesis, leading to disastrous failures in agricultural productivity. Staple crops such as maize, wheat, and rice could face failures exceeding 90%, even in temperate zones [106]. Furthermore, disturbances in worldwide trade and food delivery systems due to geopolitical uncertainty would remarkably impair food shortage and malnutrition in food-insecure territories [112]. Adopting these risks requires robust strategies, including progressing resilient crop varieties, improving global food detachments, and encouraging international collaboration to mitigate the long-term shocks of such catastrophic occurrences [113, 114].

Table 2. The crucial link between agricultural policy and global food security

Regulation category	Specific regulations	Description	Impact on global food security	Examples
Food safety regulations	Pesticide residue limits	Set maximum residue levels for pesticides in food	Ensures food safety and reduces health risks	European Union (EU) regulation 396/2005 [72, 80]
	Contaminant limits	Regulates levels of heavy metals, mycotoxins, etc.	Prevents foodborne illnesses and protects public health	Codex Alimentarius standards [78]
	Genetically modified organism (GMO) labeling	Requires labeling of genetically modified foods	Informs consumers and supports market transparency	US GMO labeling regulations [71, 74]
Environmental sustainability	Soil conservation	Encourages practices to maintain soil health	Preserves soil fertility and prevents erosion, supporting long-term productivity	US Soil Conservation Act [39, 74, 77]
	Water use regulations	Controls agricultural water extraction and use	Ensures sustainable water use, preventing shortages and environmental degradation	EU Water Framework Directive [72, 81, 115, 116]
	Biodiversity protection	Protects natural habitats and species diversity	Maintains ecosystem services crucial for agriculture, like pollination and pest control	Convention on Biological Diversity [73, 76]

Table 2. The crucial link between agricultural policy and global food security (*continued*)

Regulation category	Specific regulations	Description	Impact on global food security	Examples
Economic stability and market access	Agricultural subsidies	Provides financial support to farmers	Enhances agricultural productivity and stabilizes farm incomes	US Farm Bill subsidies [75, 82]
	Trade regulations	Sets tariffs and trade barriers on agricultural products	Influences global food distribution and market access	World Trade Organization (WTO) Agreement on Agriculture [27, 28]
	Price stabilization	Implements minimum support prices (MSPs) and buffer stocks	Protects farmers from price volatility and ensures a stable food supply	India's MSP system [59, 93, 114]
Research and development	Funding for agricultural research and decelopment	Invests in research to improve crop varieties and farming practices	Drives innovation and enhances agricultural productivity and resilience	Consultative Group on International Agricultural Research (CGIAR) programs [18]
	Extension services	Provides farmers with access to new knowledge and technologies	Improves farming practices and boosts productivity	US Cooperative Extension Service [54, 77, 82]
Social equity and rural development	Land tenure security	Ensures farmers have secure land ownership or usage rights	Encourages investment in land and sustainable farming practices	Kenya's National Land Policy [48, 117]
	Gender equality in agriculture	Promotes equal access to resources and opportunities for women	Enhances productivity and food security by empowering women farmers	Food and Agriculture Organization (FAO) Gender Strategy [1, 78, 118]
	Rural infrastructure investment	Develops roads, storage facilities, and market access	Reduces post-harvest losses and improves food distribution efficiency	India's Pradhan Mantri Gram Sadak Yojana (PMGSY) Rural Road program [119–121]
Food security programs	School feeding programs	Provides meals to schoolchildren	Improves child nutrition and education outcomes	Brazil's National School Feeding Program [59, 122]
	Food aid and assistance	Supplies food to regions in crisis	Addresses acute food insecurity and prevents hunger	World Food Program operations [20, 76]
Climate change mitigation and adaptation	Climate-smart agriculture	Promotes practices that reduce emissions and increase resilience	Enhances the sustainability of food systems in the face of climate change	FAO Climate-Smart Agriculture Sourcebook [30, 123–125]
	Carbon farming incentives	Rewards farmers for sequestering carbon in soils	Mitigates climate change and supports sustainable agriculture	Australia's Carbon Farming Initiative [48, 59, 79]
Health and nutrition	Nutrition labeling	Mandates disclosure of nutritional information on food products	Helps consumers make informed choices and promotes public health	US Food and Drug Administration (FDA) Nutrition Labeling [12, 13, 126]
Fortification regulations		It requires the addition of essential vitamins and minerals to food	Addresses micronutrient deficiencies and improves public health	World Health Organization (WHO) fortification guidelines [29]

Future directions on agriculture and global food security

Development of climate-resilient crops and precision agriculture

Future research should prioritize advanced breeding techniques and biotechnological innovations to develop climate-resilient crop varieties capable of withstanding drought, flooding, and extreme temperatures. Unraveling the genetic basis of these traits can enable the creation of crops that are better adapted to the challenges posed by changing climate conditions [55, 86, 127]. Additionally, leveraging data-driven technologies such as remote sensing and real-time monitoring systems can revolutionize crop health and soil condition management. Integrating big data analytics, artificial intelligence (AI), and machine learning (ML) holds immense potential to optimize agricultural inputs such as water, fertilizers, and pesticides, improving resource efficiency and boosting productivity. Research should also promote agroecological practices, including crop rotation, intercropping, and agroforestry, to enhance soil fertility, manage pests naturally, and increase biodiversity [107]. These practices support ecological sustainability and provide socio-economic benefits to smallholder farmers, which warrant further exploration. Sustainable nutrient management must be another priority area for future studies. Emphasis should be placed on developing biofertilizers, organic soil amendments, and techniques to enhance soil carbon sequestration, reducing reliance on chemical fertilizers while improving soil health. Additionally, IPM strategies that combine biological, cultural, and mechanical control methods with minimal pesticide use should be further investigated. Research into the role of natural predators and biocontrol agents in reducing pest populations can provide ecologically sound solutions for pest management. By addressing these critical areas, we can advance agricultural sustainability, resilience, and productivity, ultimately contributing to global food security in the face of growing environmental and socio-economic challenges.

Reducing food loss, waste, and policy

Advancing innovative technologies and practices to reduce post-harvest losses, particularly in developing countries, is critical for enhancing global food security. Research should focus on improving storage, packaging, and transportation methods and developing strategies to minimize food waste at the consumer level [113]. Additionally, evaluating the sustainability of global and local food supply chains is essential, emphasizing reducing environmental footprints, promoting fair trade practices, and ensuring equitable compensation for smallholder farmers. Studies should also investigate methods to enhance traceability and transparency in food systems, fostering greater accountability and fairness. As urbanization accelerates, research into the potential of urban agriculture to address food security challenges is increasingly essential. Investigations should assess the economic feasibility, environmental sustainability, and social implications of integrating urban farming into city planning. Simultaneously, the role of women in agriculture and food security must be explored, with strategies aimed at empowering female farmers by addressing gender disparities in access to resources, education, and decision-making. Understanding and addressing the challenges smallholder farmers face, who produce a significant portion of the world's food, is paramount [128]. Research should explore innovative approaches to improving access to markets, credit, and technology while enhancing their resilience to economic and environmental shocks. Moreover, examining the influence of policy frameworks and governance structures on agricultural practices and food security outcomes is essential. This includes evaluating the effectiveness of existing policies and designing new frameworks that promote sustainable agriculture, fair trade, and food sovereignty [105]. Biofortification should be a research priority, focusing on developing crops enriched with essential nutrients such as vitamins and minerals through conventional breeding and genetic engineering. Such advancements can significantly improve the nutritional quality of staple crops, particularly in regions facing micronutrient deficiencies [104]. Diversifying agricultural production and promoting the consumption of nutrient-dense foods, including fruits, vegetables, legumes, and animal-source products, is also crucial. Studies should investigate the cultural, economic, and environmental factors influencing dietary habits and their implications for food systems. Finally, there is a pressing need to develop and refine tools for assessing food and nutrition security at household and community levels. These tools can help identify vulnerable populations, guide interventions, and improve nutritional outcomes. By addressing these research priorities, we can foster resilient, equitable, and sustainable food systems that meet the dietary needs of a growing global population [91].

Impact investment and agriculture finance

Advancing innovative financing mechanisms is essential for supporting sustainable agricultural practices and enhancing the resilience of farming systems. Research should focus on models such as impact investing, microfinance, and public-private partnerships that enable farmers to access the capital needed to adopt sustainable technologies and practices [129]. Developing agricultural insurance products and risk management tools is crucial to protect farmers against the financial impacts of climate change, market volatility, and other uncertainties. Studies could emphasize the design and implementation of index-based insurance schemes and other tailored financial instruments to meet the specific needs of smallholder farmers [130]. Another critical area of research is the role of digital platforms in delivering agricultural extension services, especially in remote and underserved areas. These platforms can facilitate the timely dissemination of information on weather, pest management, market trends, and best practices, empowering farmers to make informed decisions. Furthermore, blockchain technology offers promising opportunities to enhance transparency and traceability in food supply chains. Research should explore its potential to improve food safety, reduce fraud, and promote fair trade practices. Addressing these research priorities can contribute to developing innovative financial, technological, and policy tools that promote sustainable agriculture, improve farmers' livelihoods, and ensure more transparent and equitable food systems [131].

Internet of Things in agriculture

Integrating Internet of Things (IoT) technologies in agriculture holds immense potential for monitoring and optimizing agricultural processes, thereby enhancing efficiency and productivity. Key research areas include developing and applying intelligent sensors, automated irrigation systems, and precision livestock farming. These technologies can significantly improve resource utilization, reduce waste, and support data-driven decision-making in farming systems. Future agriculture and food security research must embrace a holistic and interdisciplinary approach, incorporating technological, ecological, social, and economic dimensions. Addressing the multifaceted challenges of global food systems requires innovative solutions that enhance agricultural productivity while promoting sustainability and resilience. Such efforts are critical for food security amid growing environmental and socio-economic pressures. This comprehensive research agenda aligns with the United Nations SDGs, particularly SDG 2: Zero Hunger. By advancing IoT-driven innovations and fostering interdisciplinary collaboration, research can contribute to achieving sustainable and equitable food systems that leave no one behind.

Conclusions

In conclusion, the interplay between agriculture, food security, and sustainability is central to addressing the growing challenges of population growth, climate change, and resource limitations. Sustainable agricultural practices, such as precision farming, agroecology, and crop diversification, offer viable pathways to enhance productivity while minimizing environmental degradation. Integrating innovative technologies, including genetic engineering, digital agriculture, and water management systems, is equally critical to optimizing resource use and mitigating risks. Achieving global food security demands collaborative efforts among policymakers, researchers, and stakeholders to establish resilient food systems prioritizing equitable access, economic viability, and environmental stewardship. The agricultural sector can ensure long-term food security while preserving the planet's ecological integrity by balancing productivity and sustainability.

Abbreviations

CSA: climate-smart agriculture

FAO: Food and Agriculture Organization

IoT: Internet of Things

IPM: integrated pest management

SDG: Sustainable Development Goal

Declarations

Author contributions

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Conflicts of interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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