CHAPTER 11

Climate Shocks and Food System Vulnerability: Pathways to Resilience in a Changing World

Saba Shamim[1], Sarah Aleem[1], Umamah Ahmed[1], Ayesha Wasti[1], Amina Yaqoob[1], Hadia Islam[1] & Ayisha Aman Ullah[1]
[1]Department of Biotechnology, Jinnah University for Women, Karachi, Pakistan
Corresponding author's email: ayisha.aman@juw.edu.pk, ayisha.aman24@gmail.com

Abstract:

Reshaping global food systems calls for a coordinated, systems-level strategy that tackles sustainability, equity, and food security together rather than in isolation. Five linked action tracks anchor this effort: securing access to safe, nutritious food; encouraging sustainable consumption; advancing production that benefits rather than depletes nature; supporting equitable livelihoods; and building resilience against shocks and long-term stresses. The UN Food Systems Summit's fifth Action Track singles out resilience as a priority, given the mounting pressures that climate change, population growth, environmental degradation, and shrinking resources place on food supplies. A food system can be considered resilient when it can foresee disruptions, buffer their effects, adapt, and ultimately reorganize in response to shifting risks. This capacity has to be built at every level, from households and local communities up to national governments and international institutions, all while protecting the economic, social, and environmental base that long-term food security depends on. Reaching this goal involves managing difficult trade-offs: balancing urgent humanitarian relief against longer-term development goals, aligning mitigation with adaptation, weighing the benefits and risks of globalization, and raising agricultural output and rural incomes without eroding environmental integrity. Smallholder farmers in marginal, climate-exposed regions feel these tensions most acutely, and addressing them calls for coordinated action across governments, communities, and both public and private stakeholders. Since resilience looks different in every context, no single blueprint applies everywhere; instead, durable food systems emerge from adaptive, evidence-based, and collaborative approaches that combine innovation, inclusive governance, and partnerships that cut across sectors.

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1. Introduction

Climate change is undermining food security and dietary quality through a wide range of pathways, leaving vulnerable populations on every continent exposed to multiple forms of malnutrition. Poor-quality diets remain a leading driver of illness and death worldwide (Afshin *et al*., 2019). Roughly 690 million people currently go hungry, and this figure is projected to climb past 840 million by 2030 (FAO, 2020). In 2020 alone, 149.2 million children under five were stunted and 45.4 million were wasted, outcomes linked in part to poor diets, while 38.9 million children in the same age group were classified as overweight (WHO, 2021). These patterns stem partly from entrenched inequality and food systems that are not built to meet everyone's nutritional needs. Climate change is not the only external stressor at play; pandemics have compounded the problem, and COVID-19 in particular was projected to push an additional 83–132 million people into undernourishment by 2020 (WHO, 2021).

Climate change compounds the fragility of already unsustainable food systems, acting directly on soil fertility, rainfall patterns, crop yields, and the nutrient and anti-nutrient composition of food, all of which lowers the macro- and micronutrients reaching the global food supply. Indirect effects add further strain: shifting pest pressures raise the risk of spoilage and food-safety hazards at every stage of the food chain, from production through post-harvest handling to consumption, with knock-on consequences for human

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nutrition (Parfitt *et al*., 2010; Tirado *et al*., 2010; Hodges *et al*., 2011). Because this relationship between food systems and climate change runs in both directions and is further complicated by pandemics, quantifying its overall effect on human health remains a persistent challenge.

This narrative review draws on discussions from a Technical Meeting held by the International Atomic Energy Agency (IAEA, 2020) from 19 to 21 October 2020, convened to assess how effective food-based approaches are at improving diet quality within rapidly evolving food systems. The chapter traces how food systems and community-level dietary patterns have shifted over time, examines the reciprocal cycle linking food systems and climate change in terms of vulnerability and resilience, and analyzes how these dynamics affect diet quality, nutrient adequacy, and malnutrition risk. It closes by highlighting the need for measurement tools capable of tracking and evaluating the food system's different components at both micro and macro levels (Figure 11.1).

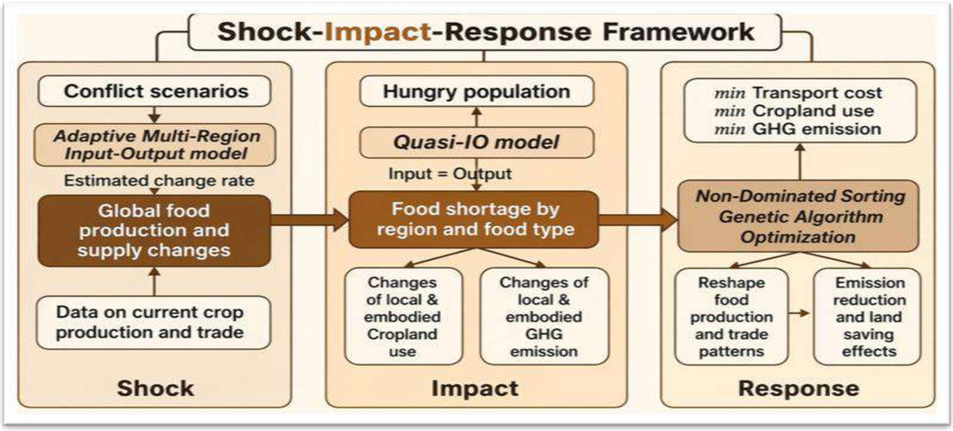

Figure 11.1: Shock–Impact–Response Framework in Food Systems

2. The Impact of Climate Change

Within the lower troposphere, the condensation of water vapor into precipitation releases latent heat that dominates the overall pattern of tropospheric diabatic heating (Trenberth *et al*., 2005). Water vapor is also the single largest gaseous contributor to infrared opacity in the atmosphere, responsible for roughly 60% of the natural greenhouse effect under clear-sky conditions (Kiehl & Trenberth, 1997), and it produces the strongest positive feedback among the variables represented in climate change model projections (Held & Soden, 2000; Karl & Trenberth, 2003).

2.1. Drought and Its Environmental Consequences

Because it develops slowly and persists for extended periods, drought is comparatively straightforward to track. Numerous indices exist, but many analyses rely on the Palmer Drought Severity Index (PDSI), which combines monthly precipitation totals with average temperatures. PDSI records dating from the mid-twentieth century reveal a pronounced drying trend across much of the Northern Hemisphere since the 1950s, most visibly over Southern Eurasia, Northern Africa, Canada, and Alaska, while Eastern North and South America moved in the opposite direction. Southern Hemisphere land surfaces, by contrast, were relatively wet in the 1970s, drier in the 1960s and 1990s, and trended drier overall between 1974 and 1998. Declining land precipitation since the 1950s appears to be the primary driver of these trends, though substantial surface warming over the past two to three decades has likely added to the drying by increasing atmospheric moisture demand. Drought has intensified notably across Africa, Southern Asia, the Southwestern United States, Australia, the Mediterranean basin (both Southern Europe and Northern Africa), and the Amazon. Dai *et al*. (2004) found that the global extent of severely dry land, defined as areas with a PDSI below −3.0, more than

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doubled after the 1970s, an expansion that was initially tied to an El Niño Southern Oscillation (ENSO)-related drop in land precipitation and later driven mainly by rising surface temperatures.

Figure 11.2: Drought-Affected Landscape and Water Scarcity

Case Study: California's 2012–2016 drought ranks among the most severe on record, the product of years of below-average rainfall, persistent high-pressure systems, and elevated temperatures tied to climate variability and warming. The result was severe soil-moisture loss, shrinking surface water supplies, and heavy groundwater depletion as irrigation demand climbed. Ecologically, the drought stressed vegetation, drove forest dieback, raised wildfire frequency, and degraded aquatic habitats; agriculturally, it caused major crop losses and economic damage as farmers cut production and leaned more heavily on groundwater. The episode illustrates how rising temperatures amplify drought severity by increasing evaporation and atmospheric moisture demand, consistent with the broader global pattern of intensifying drought risk under climate change (Flint *et al*., 2018; Ullrich *et al*., 2018).

2.2. Flooding and Hydrological Extremes

Flood generation and runoff behave as a highly nonlinear system, shaped by the natural spatial and temporal variability of meteorology, topography, soil, vegetation, groundwater conditions, and channel drainage. This makes precise quantitative statements about climate change's effect on flooding and runoff difficult to establish with confidence. What follows is therefore a qualitative assessment grounded in current scientific understanding, drawing on established physical principles and the interpretation of available measurements.

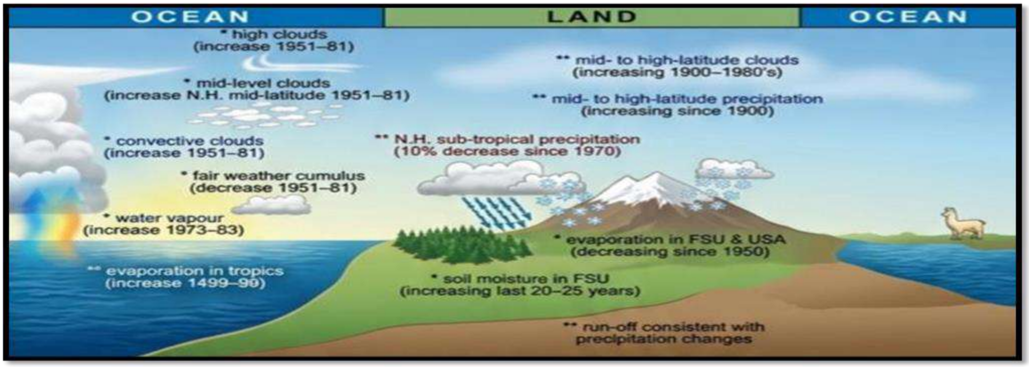

Figure 11.3: Global Water Cycle and Climate Change

Assessing flood-loss risk requires examining meteorological and hydrological conditions, river hydraulics, and land use separately, since any of these can raise flood damage risk when negative interactions and synergies emerge among them. Meteorological conditions carry the greatest weight where climate change is

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concerned, but catchment vegetation and soil conditions also matter: because they govern water retention and evaporation, climate change can alter them in ways that feed back into how floods develop.

2.3. Impact of Soil Salinity on Agricultural Sustainability

Soil salinity refers to the buildup of soluble salts, chiefly sodium, calcium, and magnesium, in the soil profile, typically caused by saline irrigation water, poor drainage, high evaporation rates, and rising water tables. In dry and semi-arid climates, rapid surface evaporation leaves salts behind in the root zone, and capillary rise of saline groundwater combined with insufficient leaching compounds the buildup. High salinity impairs plants' ability to take up water, triggers ion toxicity, and disrupts nutrient uptake, leading to stunted growth, lower yields, and progressive soil degradation; excess sodium can also break down soil structure, reducing permeability and aeration. Management options include improved drainage, salt leaching, gypsum amendments, more efficient irrigation, and the cultivation of salt-tolerant varieties (Mohanavelu *et al*., 2021; Stavi *et al*., 2021).

Climate change is measurably worsening soil salinity across agricultural regions, particularly in arid, semi-arid, and coastal zones. Tracking salinity levels is essential for gauging its extent, spotting trends, and designing effective irrigation and crop management responses; tools such as proximal sensors and remote sensing, pioneered by the U.S. Salinity Laboratory, now allow salinity to be assessed at scales ranging from individual fields to entire regions. Case studies from California's San Joaquin Valley and Minnesota's Red River Valley point to shifting weather patterns, shallow water tables, seawater intrusion, and poor-quality irrigation water as the main drivers of rising salinity, underscoring the need for robust monitoring systems at local through global scales to manage and limit its impact on agriculture (Corwin, 2021).

2.4. Influence of Heat Stress on Agricultural Production

Heat waves, extended spells of extreme temperature often paired with high humidity, have become a fast-growing focus of climate change research; a review of more than 8,000 studies found that heat-wave research output has doubled over the past five years. Landmark events in 1995 and 2003, particularly across the USA, Europe, and Australia, exposed serious consequences ranging from drought and urban heat-island effects to surges in hospital admissions and mortality. Of particular concern is the possibility that rising temperature and humidity, captured by the wet-bulb temperature metric, could approach the limits of human survivability by the century's end, a finding that underscores the urgency of better risk assessment and adaptation planning for extreme heat (Marx *et al*., 2021).

2.5. Future Projections of Tropical Cyclone Activity in a Warming Climate

Understanding of how climate change influences tropical cyclone activity has advanced considerably in recent years, though important uncertainties persist (Figure 11.4). Historical records show long-term variability in cyclone activity, with no clear multi-decadal trend in the Atlantic basin overall but a noticeable rise in storm intensity and frequency in recent decades. Climate models generally point toward fewer cyclones worldwide but stronger storms carrying heavier rainfall, while rising sea levels are expected to worsen storm-surge and flooding risk, especially in densely populated coastal zones and river deltas. Differences in data quality, modeling approaches, and emissions scenarios still produce inconsistent projections, pointing to a continuing need for more precise assessments of future cyclone risk.

Cyclone Amphan, one of the most powerful tropical cyclones ever recorded in the Bay of Bengal, offers a striking case study of how climate change may shape future cyclone behavior. Forming in May 2020, it intensified rapidly over unusually warm sea-surface temperatures before making landfall across coastal India and Bangladesh, with wind speeds exceeding 240 km/h that devastated infrastructure, agriculture, and coastal ecosystems (Rathore *et al*., 2022; Ahammed & Pandey, 2021).

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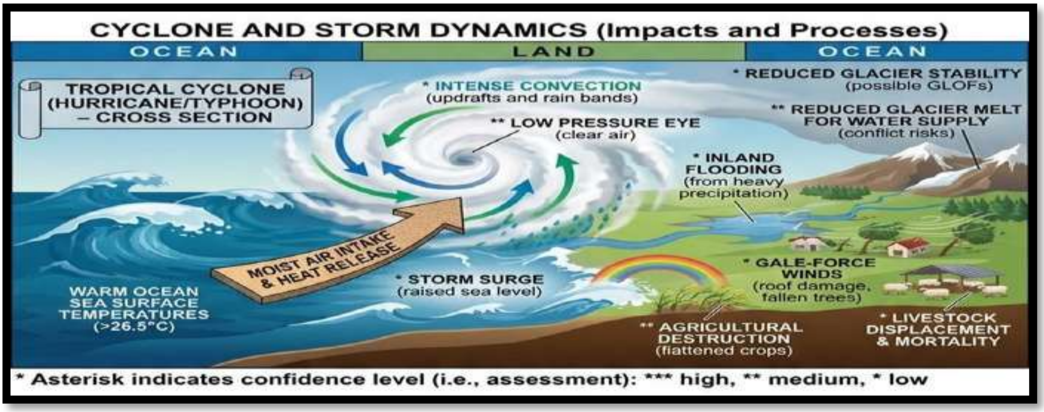

Figure 11.4: Tropical Cyclone

Researchers traced Amphan's rapid intensification to warming ocean temperatures linked to global warming: warmer sea surfaces supplied the extra energy that fueled stronger winds and heavier rainfall, while rising sea levels amplified storm-surge impacts and drove extensive flooding across low-lying coastal areas and river deltas. Millions of people were displaced, and agricultural land suffered heavy damage from saline water intrusion and flooding.

Amphan's trajectory lends support to climate model projections indicating that, even as the total number of tropical cyclones may decline globally, the intensity of severe storms and their associated rainfall is likely to rise under continued warming. That said, uncertainty remains around regional cyclone frequency and the long-term accuracy of these projections, reflecting differences across climate models and observational datasets.

3. Food System and Nutritional Vulnerabilities

3.1. Food System Vulnerability

Food system vulnerability describes how susceptible food systems are to disruption from external stressors, especially climate-related shocks such as drought, flooding, heatwaves, and erratic rainfall. This susceptibility spans several interconnected dimensions, including agricultural and economic ones, which are examined in turn below (FAO, 2020; IPCC, 2022).

3.2. Agricultural Vulnerability

Agricultural systems are acutely sensitive to climatic variability and extreme weather, both of which bear directly on crop productivity and food availability. Drought, flooding, and extreme temperatures can destroy crops before harvest, while soil degradation, erosion, salinization, and nutrient depletion further erode fertility and limit sustainable production. Water scarcity, driven by irregular rainfall and shrinking freshwater resources, restricts irrigation and pushes farmers toward greater reliance on rain-fed agriculture. Together, these pressures weaken agricultural resilience and put long-term food security at risk (IPCC, 2022; Wheeler & von Braun, 2013).

3.3. Economic Vulnerability

Climate-related disturbances also carry substantial economic risk for food systems. Falling agricultural output tends to drive food price volatility, pushing staple foods out of reach for low-income households, while farmers and agricultural laborers lose income as productivity falls and yields become unpredictable, weakening rural livelihoods. Extreme weather also disrupts transport, storage, and trade, straining supply

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chains and market stability. The cumulative economic fallout deepens food insecurity and falls hardest on communities with the least capacity to adapt (FAO, 2020; World Bank, 2021).

3.4. Nutritional Vulnerability

Older adults face a distinct form of nutritional vulnerability, arising when diminished physical reserves limit their capacity to recover from illness or stress, raising the odds of medical complications, prolonged hospitalization, and long-term care dependence. This vulnerability can emerge at home, in hospital, or in residential care settings alike. Individualized nutritional care can lessen this risk and strengthen resilience, and meeting older adults' specific dietary needs is essential to helping them manage both acute and chronic health challenges and, ultimately, to preserve their overall health and quality of life (Baumgartner *et al*., 2021; Starr *et al*., 2015).

4. Structure–Function Dynamics in Complex Food Matrices

How a food product behaves is governed largely by its structure, that is, how components such as water droplets, oil droplets, gas cells, proteins, carbohydrates, and fat crystals are arranged and how they interact with one another. These structural features, visible through imaging techniques, are found across a wide range of foods, from bread and cheese to yoghurt, milk, and ice cream, and each component contributes in its own way to the final product's texture, consistency, and stability.

Interactions among these components, protein–protein, protein–carbohydrate, and fat-crystal interactions among them, are what ultimately build a food's structure, and they shape how the product performs at a larger scale, including its appearance, mouthfeel, and overall functionality. A solid grasp of this structure–function relationship supports the development of new methods for producing food that is higher quality, more nutritious, and more appealing (Heertje, 2013).

5. Socioeconomic and Gender Dimensions of Vulnerability

The effects of climate change are not shared equally; rather, they compound existing social and economic inequalities and fall disproportionately on already-vulnerable populations (Figure 11.5).

5.1. Inequality and Food Access

Food insecurity and limited access to affordable, nutritious food are closely tied to poor dietary outcomes and a heightened risk of chronic conditions such as cardiovascular disease, diabetes, and cancer. These burdens fall disproportionately on low-income populations and racial or ethnic minority groups, who are more likely to live in under-resourced food environments. Despite a growing body of research, important gaps remain in understanding exactly how food insecurity interacts with neighborhood conditions to produce these health disparities, underscoring the need for targeted interventions and policies that improve food access and advance health equity, particularly in the context of crises such as the COVID-19 pandemic.

5.2. Gendered Impacts

Crises such as COVID-19 tend to affect men and women differently, with women shouldering disproportionate social and economic burdens. A longitudinal study of informal settlements in Nairobi, Kenya, found that women experienced higher rates of food insecurity, greater exposure to domestic violence, and reduced access to healthcare relative to men, with those who lost income particularly likely to skip meals and delay medical care. These findings point to the need for gender-sensitive policies that support women's recovery, protect their livelihoods, and advance longer-term gender equality (Pinchoff *et al*., 2021).

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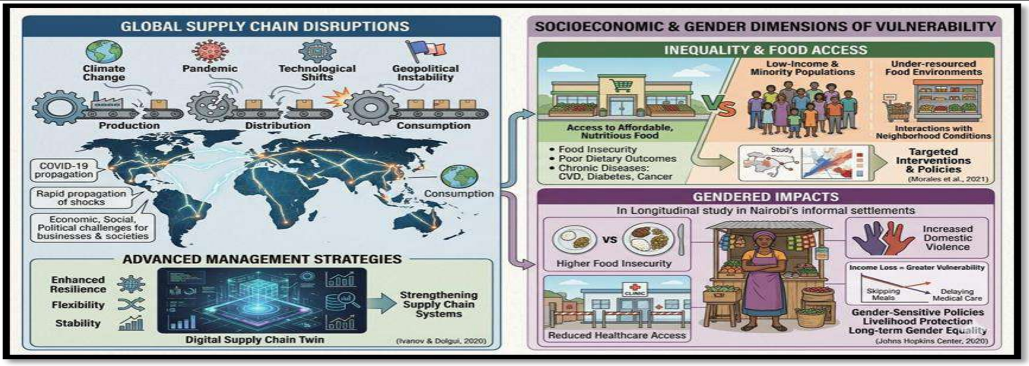

Figure 11.5: Global Supply Chains and Socioeconomic Vulnerability

5.3. Urban Vs. Rural Vulnerability

Urban environments offer real economic and educational advantages, but they also carry heightened mental health risks, including anxiety, depression, and substance abuse, driven by factors such as social inequality, pollution, and weakened community networks, especially in deprived urban areas (Figure 11.6). Exposure to these conditions across the life course, from childhood through young adulthood, can leave lasting marks on mental health and wellbeing. Reducing this vulnerability calls for targeted urban planning, stronger social support systems, and mental health interventions that improve quality of life (Wiers *et al*., 2025; Collins *et al*., 2024).

6. Resource Nexus: Water-Energy-Food Interactions

The water-energy-food (WEF) nexus framework highlights just how interconnected these essential resources are, and how difficult it is to meet rising demand for all three at once. Population growth, urbanization, and climate change are the principal drivers of resource scarcity, and management approaches that treat water, energy, and food as separate sectors have repeatedly proven inadequate, often generating conflict rather than resolving it. What is needed instead are integrated, flexible strategies capable of managing these resource interactions sustainably (Machell *et al*., 2015).

6.1. Interconnected Resource Systems

The Social-Ecological Systems (SES) framework has evolved as a tool for understanding resource governance and the interplay among ecological, social, and institutional factors. Research applying this framework points to recurring governance failures, poor coordination among actors, decentralization implemented without adequate support, and insufficient resource allocation, all of which reinforce the case for systematic, integrated approaches to managing interconnected resource systems (Bourceret *et al*., 2021).

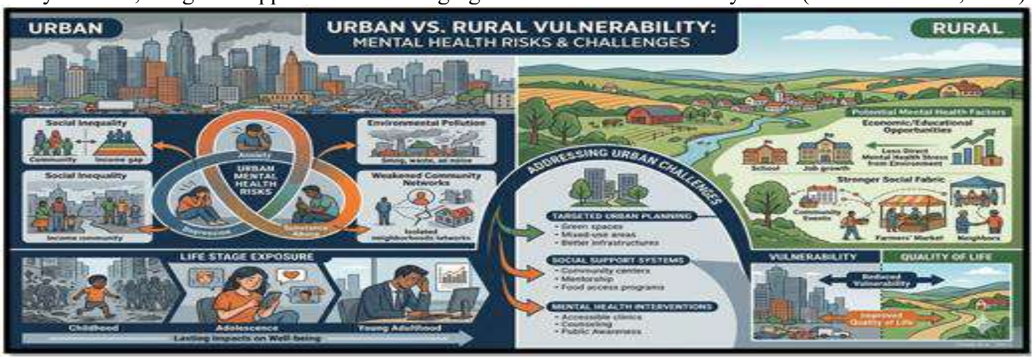

Figure 11.6: Urban vs. Rural Vulnerability

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6.2. Climate-Induced Resource Conflicts

Climate change is a significant driver of resource scarcity, particularly for water and arable land, which in turn deepens socio-economic inequality and fuels conflict. Studies from across Africa show how environmental scarcity and relative deprivation intensify tensions between groups such as farmers and herders, with these pressures often triggering displacement and instability, especially in regions like the Sahel and the Lake Chad Basin, where weak governance structures make the conflicts harder to contain. Addressing this requires integrated strategies spanning stronger governance, sustainable livelihoods, climate adaptation, and early warning systems (Osazuwa *et al*., 2025).

6.3. Integrated Resource Management

Integrated Water Resources Management (IWRM) stands out as a central approach for strengthening water governance and long-term sustainability. Comparative research shows that regions applying IWRM tend to manage resources markedly better, largely because effective water governance depends on coordination among stakeholders, adherence to sound governance principles, and efficient allocation of resources — findings that reinforce the value of integrated approaches for managing complex resource systems (Katusiime & Schütt, 2020).

7. Case Studies: Regional Climate Shocks

7.1. Floods in Pakistan (2022): Systemic Breakdown

The 2022 floods in Pakistan, triggered by extreme monsoon rainfall, rank among the most severe climate-related disasters in the country's history, although limitations in climate models and natural variability leave some uncertainty around their precise causes. Importantly, climatic factors alone cannot explain the scale of devastation: structural vulnerabilities, inadequate infrastructure, unplanned settlement in flood-prone areas, weak disaster management systems, poverty, and political instability, significantly amplified the impact. The disaster underscores the importance of integrating climate adaptation with socioeconomic policy and governance reform (Waseem & Rana, 2023).

Figure 11.7: Large-Scale Flooding in Rural and Urban Areas in Pakistan

7.2. Sub-Saharan Africa: Chronic Drought Systems

Drought has grown both more frequent and more severe across Sub-Saharan Africa, deepening the region's vulnerability. Evidence points to a clear worsening trend, bringing crop failures, water scarcity, food insecurity, and mounting economic pressure in its wake. The consequences extend well beyond environmental stress to social disruption, including migration, malnutrition, disease outbreaks, and family breakdown, and current adaptation efforts by governments and non-governmental organizations remain insufficient given the scale of the problem. Building durable resilience will require better drought preparedness, more sustainable resource management, and stronger policy frameworks (Wilhite, 2000).

7.3. South Asia Heatwaves: Yield Collapse Risk

Rising greenhouse gas emissions have substantially altered global temperature and precipitation patterns, and the scientific consensus, reflected in successive IPCC assessments, confirms a strong causal link between

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human activity and global warming. By the end of the twenty-first century, global surface temperatures could rise by 3–6°C alongside a 12–14% increase in rainfall (IPCC, 2018, 2022), changes that pose serious risks to agricultural productivity, particularly in South Asia, where extreme heatwaves threaten both crop yields and food security (Figure 11.8). Regional projections show substantial variation in temperature and precipitation across different parts of Africa as well, further illustrating how unevenly climate change is felt. Uncertainties remain, but the overall trend points toward growing risk of yield collapse under extreme climatic conditions (Knox *et al*., 2012; IPCC, 2018).

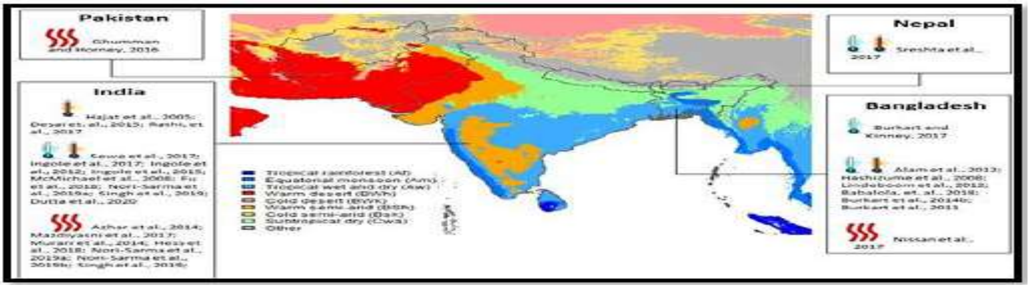

Figure 11.8: South Asian Climate Vulnerability Map

7.4. Global Supply Chain Disruptions

Global supply chains are growing more vulnerable to disruption from climate change, pandemics, technological shifts, and geopolitical instability. COVID-19 in particular showed how quickly shocks can propagate through interconnected systems, disrupting production, distribution, and consumption alike, and generating significant economic, social, and political fallout for businesses and societies. Research points to the value of identifying recurring disruption patterns and adopting advanced management tools, such as digital supply chain twins, to build resilience, flexibility, and stability, making supply chain strengthening a critical task for navigating an increasingly uncertain global environment (Ivanov & Dolgui, 2020).

8. Biotechnological Innovations in Crop Adaptation to Climate Change

8.1. CRISPR and Gene Editing Technologies

CRISPR–Cas genome editing has emerged as a powerful biotechnological tool for developing climate-resilient crops, allowing precise modification of genes linked to tolerance against both abiotic and biotic stresses (Figure 11.9).

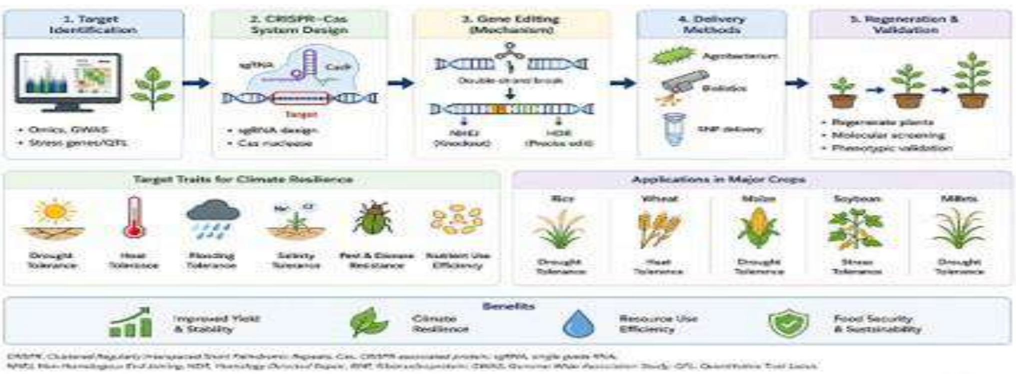

Figure 11.9: CRISPR and Gene Editing Technologies for the Development of Climate Resilient Crops

The process typically proceeds through target-gene identification, guide RNA (sgRNA) design, CRISPR–Cas-mediated editing, delivery of the editing machinery into plant cells, and regeneration of edited plants for

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phenotypic evaluation. It has been applied successfully to improve tolerance to drought, heat, salinity, flooding, and disease, as well as nutrient-use efficiency, in major crops including rice, wheat, maize, soybean, and millets. Relative to conventional breeding, CRISPR-based editing offers greater precision, shorter breeding cycles, and the option of producing transgene-free cultivars, which together accelerate crop improvement and strengthen agricultural productivity and food security under a changing climate (Chavhan *et al*., 2025; Chen *et al*., 2024; Kumar *et al*., 2023; Rai *et al*., 2023; Ceasar & Ignacimuthu, 2023; Yadav *et al*., 2023; Wang *et al*., 2022).

8.2. Contribution of PGPR, Mycorrhizae, And Nitrogen-Fixing Bacteria to Agriculture (Biofertilizers)

Beneficial soil microorganisms contribute substantially to plant health, soil fertility, and resilience against environmental stress. Plant Growth-Promoting Rhizobacteria (PGPR) boost nutrient uptake, stimulate root development, and improve tolerance to drought and salinity, while mycorrhizal fungi enhance water absorption, strengthen soil structure, and increase phosphorus availability. Nitrogen-fixing bacteria such as *Rhizobium* lessen dependence on synthetic nitrogen fertilizers by converting atmospheric nitrogen into forms plants can use. Collectively, these microbial innovations support sustainable agriculture while limiting environmental degradation (Chattaraj *et al*., 2025; Fasusi *et al*., 2023; Al-Turki *et al*., 2023; Sagar *et al*., 2021).

8.3. Biological Alternatives to Synthetic Agrochemicals in Sustainable Farming (Biopesticides)

Biopesticides, derived from natural sources such as bacteria, fungi, algae, and plant extracts, offer an environmentally safer alternative for pest and disease control. By reducing reliance on synthetic agrochemicals, they help limit soil and water pollution and support ecological balance, making them an essential component of climate-smart agriculture (Verma *et al*., 2024; Swapan *et al*., 2023; Sehrawat *et al*., 2021; Fenibo *et al*., 2022).

8.4. Sustainable Food Processing Through Fermentation Biotechnology

Fermentation is a valuable biotechnological tool for improving food preservation, nutritional quality, and food security. Microbial fermentation extends the shelf life of perishable products, cuts post-harvest losses, and improves digestibility and nutrient bioavailability, while fermented foods also support gut health and food safety by suppressing pathogenic microorganisms. In resource-limited settings without reliable refrigeration, fermentation offers a low-cost, sustainable way to preserve food quality and reduce waste (Vermelho *et al*., 2025; Nascimento & Barros, 2025; Aguirre-Garcia *et al*., 2024; Siddiqui *et al*., 2023).

9. Synthetic Biology in Food Systems and Key Applications

Synthetic biology is emerging as a powerful means of tackling global food security challenges by enabling the design of biological systems that produce sustainable, functional food products. Applications range from microbial “cell factories” that manufacture food components, additives, and nutrients to alternatives for conventional animal-based products such as meat, milk, and sweeteners (Figure 11.10). Recent progress in the field points to its potential to improve food safety, nutritional quality, and environmental sustainability, positioning synthetic biology as a critical tool for the food systems of the future (Lv *et al*., 2021).

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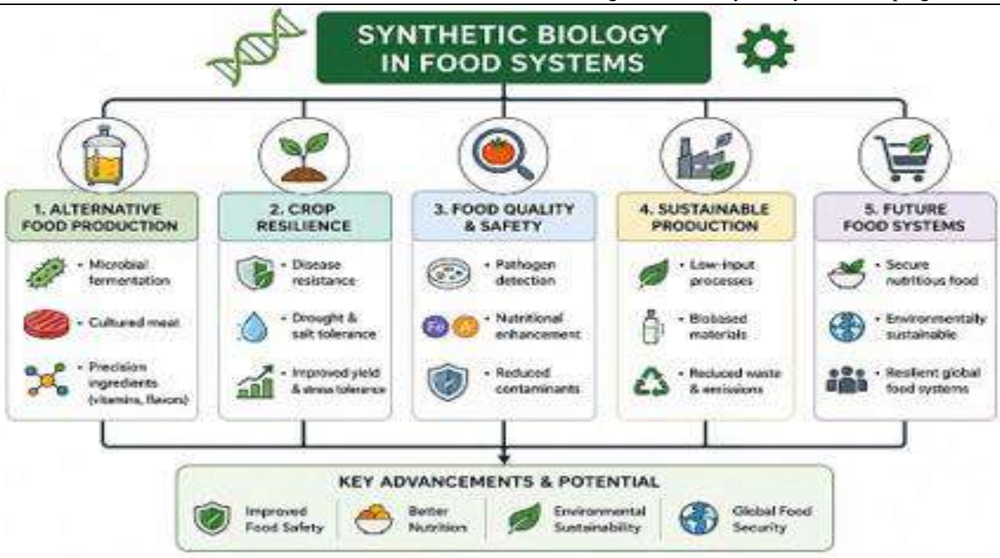

Figure 11.10: Synthetic Biology in Food Systems

9.1. Microbiome Engineering

Microbiome engineering seeks to modify microbial communities in ways that enhance their functional capabilities, but the complexity of microbial interactions and the limited availability of effective engineering tools make this a difficult undertaking. Recent studies propose combining top-down and bottom-up approaches to construct synthetic microbiomes with enhanced function.

For instance, natural microbiomes have been steered toward improved bioremediation performance through herbicide treatments combined with degrader inoculation. Computational tools such as SuperCC further support this work by enabling analysis of metabolic interactions and informing the design of synthetic microbial communities, offering a practical framework for future applications (Zhang *et al*., 2026).

9.2. Precision Fermentation and Food

Precision fermentation is an emerging cellular-agriculture technology that uses microorganisms to produce alternative proteins, directly addressing two major concerns with conventional food systems: environmental impact and animal welfare. Through optimized microbial strains and fermentation processes, it is now possible to produce animal-like proteins, including milk and egg proteins, and the approach holds considerable promise for advancing sustainable, scalable, and innovative food production (Knychala *et al*., 2024).

10. Climate-Smart Agriculture and AI

Climate change affects agriculture everywhere, but effective adaptation is inherently location-specific and needs to be validated at the smallholder level. Climate-smart agriculture (CSA) practices applied within integrated crop-livestock farming systems have been shown to raise both productivity and income (Bhatnagar *et al*., 2024).

10.1. Early Warning Systems

As climate change accelerates, societies face growing exposure to disaster and stress, underscoring the urgent need for effective early warning systems (EWS) that can monitor, assess, and communicate risk in support of resilience and sustainable development. Even so, challenges persist around hazard forecasting, risk communication, and decision-making (Rokhideh *et al*., 2025).

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10.2. Digital Agriculture and AI-Driven Innovations

Agriculture remains vital for economic growth, yet population growth, climate change, and resource constraints are making production increasingly challenging. Precision agriculture responds to this by combining machine learning (ML) and the Internet of Things (IoT) to improve efficiency and sustainability: ML models help predict soil conditions and crop yields and detect diseases and weeds, computer vision supports crop monitoring, and sensor-based analysis improves livestock health and behavior management. Smart systems for automated irrigation and harvesting further reduce labor requirements. Taken together, ML-driven farming raises productivity, quality, and sustainability (Sharma *et al*., 2021; AbdelRahman, 2023).

11. Policy Frameworks and Governance Systems

11.1. Climate Policy Integration Frameworks

Responding effectively to climate change requires strong policy coordination, an aim commonly pursued through policy integration. Environmental Policy Integration (EPI) has long been central to sustainable development efforts, but Climate Policy Integration (CPI) is a newer and increasingly important concept that, unlike EPI's broad integration, focuses on coordinating specific sectors toward targeted climate goals (Plank *et al*., 2021).

11.2. National-Level Policy Strategies

Environmental governance has traditionally relied on single-issue regimes with binding rules for states, yet major global challenges such as climate change, deforestation, and biodiversity loss are in practice governed through far more complex systems that combine legal and non-legal instruments and both governmental and non-governmental actors. Understanding their real impact therefore requires moving beyond simple measures of compliance and effectiveness toward a broader concept of influence over domestic policy and practice. One such framework identifies four pathways through which this influence operates: international rules, norms and discourse, market mechanisms, and direct access to domestic policymaking — together explaining how global actors shape national and firm-level action, with forest governance serving as a leading example (Bernstein & Cashore, 2012).

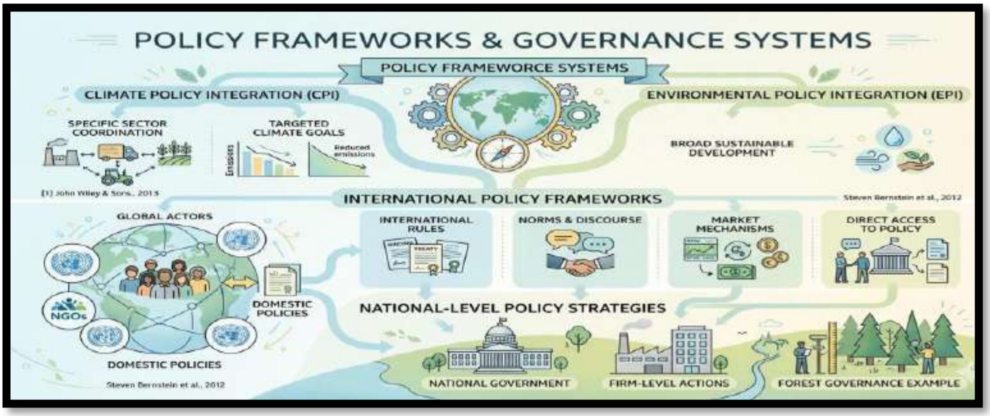

Figure 11.11: Policy Frameworks and Governance Systems

11.3. Government Policy

Government policies play a crucial role in strengthening resilience across food and agricultural systems (Akbar *et al*., 2025; Hogan & Schlenker, 2024; Bikomeye *et al*., 2021). They do so largely by setting the

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overall agenda for food security, disaster risk reduction, and climate adaptation at both national and subnational levels.

11.4. Community-Based Adaptation

People, their local cultures, and the environments they inhabit form complex, dynamic social-ecological systems that have co-evolved over time and remain continually shaped by a wide range of factors, including climate and other global changes (McMillen *et al*., 2017).

12. Future Perspectives on Transformative Food Systems

12.1. Climate-Resilient Functional Foods and Nutritional Innovation

Within modern agriculture and food science, emergent crops offer a promising route toward diversification, sustainability, and improved food security. Neglected and underutilized species (NUS) such as quinoa, amaranth, chia, moringa, and millets combine exceptional nutritional properties with strong adaptability to diverse environmental conditions, and their resilience to climate-related stress makes them valuable for sustainable agriculture, functional food development, and more diversified cropping systems. Wider adoption of these crops nonetheless remains constrained by limitations in production and processing technology, consumer awareness, and commercialization (Matías *et al*., 2024).

12.2. Dynamics of Transformational and Incremental Change

Transformational climate adaptation calls for fundamental changes in governance, institutions, and management practice in order to keep pace with the escalating impacts of climate change. Rather than treating incremental and transformational adaptation as opposing approaches, it is more useful to see how gradual, small-scale interventions can accumulate into substantial long-term transformation, achieved by scaling up successful local initiatives, integrating innovative practices, overcoming systemic barriers, and strengthening adaptive governance. This view emphasizes adaptive leadership, collaborative decision-making, and institutional flexibility as the building blocks of resilient, sustainable systems capable of responding to evolving climate challenges (Termeer *et al*., 2017).

12.3. Integrated Framework for Food System Resilience

Food system resilience is best understood as a multidimensional capacity, the ability of a food system to withstand, adapt to, and recover from environmental, economic, and social disturbances while still delivering food security and sustainability. Building this capacity means strengthening three complementary strategies: robustness to resist shocks, recovery to restore functionality once disrupted, and reorientation to adapt and transform as conditions change. Meeting these objectives requires balancing the priorities of diverse stakeholders, navigating trade-offs, and fostering inclusive governance and collaborative decision-making so that food systems remain equitable, adaptive, and future-ready (Zurek *et al*., 2022).

13. Conclusion

Climate change is fundamentally reshaping global food systems, deepening existing vulnerabilities and generating new challenges for food security, nutrition, and sustainable development. As this chapter has shown, climate-induced shocks — droughts, floods, heatwaves, soil salinity, and tropical cyclones among them — interact with socioeconomic inequality, fragile supply chains, and resource constraints to undermine the stability, availability, accessibility, and utilization of food. These impacts weigh most heavily on smallholder farmers, low-income populations, women, and communities in climate-sensitive, resource-scarce settings.

The evidence reviewed here makes clear that food system resilience cannot be achieved through isolated interventions; it demands an integrated, systems-based approach that links climate adaptation, sustainable resource management, technological innovation, and inclusive governance. Climate-smart agriculture, biotechnology, precision farming, artificial intelligence, early warning systems, and microbial and genetic innovation all offer promising ways to strengthen adaptive capacity and reduce vulnerability, but they need

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to be matched by investment in resilient infrastructure, water-energy-food nexus management, gender-responsive policy, and community-based adaptation that addresses the social dimensions of resilience.

Ultimately, building resilient food systems requires shifting from reactive crisis management toward proactive transformation. Governments, researchers, private sector actors, and local communities need to work together to develop policies and innovations that strengthen a food system's capacity to anticipate, absorb, adapt to, and recover from future shocks. Through integrated, evidence-driven, and inclusive approaches, societies can build food systems that are not only more resilient to climate change, but also more equitable, sustainable, and capable of securing adequate food and nutrition for present and future generations.

References

AbdelRahman, M. A. (2023). An overview of land degradation, desertification and sustainable land management using GIS and remote sensing applications. *Rendiconti Lincei. Scienze Fisiche e Naturali*, *34*(3), 767–808. https://doi.org/10.1007/s12210-023-01155-3

Afshin, A., Sur, P. J., Fay, K. A., Cornaby, L., Ferrara, G., Salama, J. S., ... Murray, C. J. (2019). Health effects of dietary risks in 195 countries, 1990–2017: A systematic analysis for the Global Burden of Disease Study 2017. *The Lancet*, *393*(10184), 1958–1972. https://doi.org/10.1016/S0140-6736(19)30041-8

Aguirre-Garcia, Y. L., Nery-Flores, S. D., Campos-Muzquiz, L. G., Flores-Gallegos, A. C., Palomo-Ligas, L., Ascacio-Valdés, J. A., Sepúlveda-Torres, L., & Rodríguez-Herrera, R. (2024). Lactic acid fermentation in the food industry and bio-preservation of food. *Fermentation*, *10*(3), 168. https://doi.org/10.3390/fermentation10030168

Ahammed, K. B., & Pandey, A. C. (2021). Characterization and impact assessment of super cyclonic storm AMPHAN in the Indian subcontinent through space borne observations. *Ocean & Coastal Management*, *205*, 105532. https://doi.org/10.1016/j.ocecoaman.2021.105532

Akbar, A., Darma, R., Irawan, A., Fudjaja, L., Amandaria, R., & Akzar, R. (2025). An institutional framework for enhanced food security amidst the COVID-19 pandemic: Strategic implementation and outcomes. *Journal of Agriculture and Food Research*, *21*, 101833. https://doi.org/10.1016/j.jafr.2025.101833

Al-Turki, A., Murali, M., Omar, A. F., Rehan, M., & Sayyed, R. Z. (2023). Recent advances in PGPR-mediated resilience toward interactive effects of drought and salt stress in plants. *Frontiers in Microbiology*, *14*, 1214845. https://doi.org/10.3389/fmicb.2023.1214845

Baumgartner, A., Pachnis, D., Parra, L., Hersberger, L., Bargetzi, A., Bargetzi, L., Kaegi-Braun, N., Tribolet, P., Gomes, F., Hoess, C., Pavlicek, V., Bilz, S., Sigrist, S., Braendle, M., Henzen, C., Thomann, R., Rutishauser, J., Aujesky, D., Rodondi, N., ... Schuetz, P. (2021). The impact of nutritional support on malnourished inpatients with aging-related vulnerability. *Nutrition*, *89*, 111279. https://doi.org/10.1016/j.nut.2021.111279

Bernstein, S., & Cashore, B. (2012). Complex global governance and domestic policies: Four pathways of influence. *International Affairs*, *88*(3), 585–604. https://doi.org/10.1111/j.1468-2346.2012.01090.x

Bhatnagar, S., Chaudhary, R., Sharma, S., Janjhua, Y., Thakur, P., Sharma, P., & Keprate, A. (2024). Exploring the dynamics of climate-smart agricultural practices for sustainable resilience in a changing climate. *Environmental and Sustainability Indicators*, *24*, 100535. https://doi.org/10.1016/j.indic.2024.100535

Bikomeye, J. C., Namin, S., Anyanwu, C., Rublee, C. S., Ferschinger, J., Leinbach, K., ... Beyer, K. M. (2021). Resilience and equity in a time of crises: Investing in public urban greenspace is now more essential than ever in the US and beyond. *International Journal of Environmental Research and Public Health*, *18*(16), 8420. https://doi.org/10.3390/ijerph18168420

Bourceret, A., Amblard, L., & Mathias, J. D. (2021). Governance in social-ecological agent-based models: A review. *Ecology & Society*, *26*(2). https://doi.org/10.5751/ES-12440-260238

Ceasar, S. A., & Ignacimuthu, S. (2023). CRISPR/Cas genome editing in plants: Dawn of Agrobacterium transformation for recalcitrant and transgene-free plants for future crop breeding. *Plant Physiology and Biochemistry*, *196*, 724–730. https://doi.org/10.1016/j.plaphy.2023.02.030

Chattaraj, S., Samantaray, A., Ganguly, A., *et al*. (2025). Employing plant growth-promoting rhizobacteria for abiotic stress mitigation in plants: With a focus on drought stress. *Discover Applied Sciences*, *7*, 68. https://doi.org/10.1007/s42452-025-06468-6

Chavhan, R. L., Jaybhaye, S. G., Hinge, V. R., Deshmukh, A. S., Shaikh, U. S., Jadhav, P. K., Kadam, U. S., & Hong, J. C. (2025). Emerging applications of gene editing technologies for the development of climate-resilient crops. *Frontiers in Genome Editing*, *7*, 1524767. https://doi.org/10.3389/fgeed.2025.1524767

Chen, F., Chen, L., Yan, Z., Xu, J., Feng, L., He, N., Guo, M., Zhao, J., Chen, Z., Chen, H., Yao, G., & Liu, C. (2024). Recent advances of CRISPR-based genome editing for enhancing staple crops. *Frontiers in Plant Science*, *15*, 1478398. https://doi.org/10.3389/fpls.2024.1478398

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Chrubasik-Hausmann, S., Hellwig, E., Müller, M., & Al-Ahmad, A. (2021). Antimicrobial photodynamic treatment with mother juices and their single compounds as photosensitizers. *Nutrients*, *13*(3), 710. https://doi.org/10.3390/nu13030710

Collins, P. Y., Sinha, M., Concepcion, T., *et al*. (2024). Making cities mental health friendly for adolescents and young adults. *Nature*, *627*, 137–148. https://doi.org/10.1038/s41586-023-07005-4

Corwin, D. L. (2021). Climate change impacts on soil salinity in agricultural areas. *European Journal of Soil Science*, *72*(2), 842–862. https://doi.org/10.1111/ejss.13010

Dai, A., Trenberth, K. E., & Qian, T. (2004). A global dataset of Palmer Drought Severity Index for 1870–2002: Relationship with soil moisture and effects of surface warming. *Journal of Hydrometeorology*, *5*(6), 1117–1130. https://journals.ametsoc.org/view/journals/hydr/5/6/jhm-386_1.pdf

Fasusi, O. A., Babalola, O. O., & Adejumo, T. O. (2023). Harnessing of plant growth-promoting rhizobacteria and arbuscular mycorrhizal fungi in agroecosystem sustainability. *CABI Agriculture and Bioscience*, *4*(1), 1–18. https://doi.org/10.1186/s43170-023-00168-0

Fenibo, E. O., Ijoma, G. N., & Matambo, T. (2022). Biopesticides in sustainable agriculture: Current status and future prospects. In *New and future development in biopesticide research: Biotechnological exploration* (pp. 1–53). https://www.preprints.org/frontend/manuscript/c78cfb3c4dfd658d353cfbe9f895788f/download_pub

Flint, L. E., Flint, A. L., Mendoza, J., Kalansky, J., & Ralph, F. M. (2018). Characterizing drought in California: New drought indices and scenario-testing in support of resource management. *Ecological Processes*, *7*(1), 1. https://doi.org/10.1186/s13717-017-0112-6

Food and Agriculture Organization. (2020). *The state of food security and nutrition in the world 2020*. https://openknowledge.fao.org/server/api/core/bitstreams/9a0fca06-5c5b-4bd5-89eb-5dbec0f27274/content

Heertje, I. (2013). Structure and function of food products: A review. *Food Structure*, *1*(1), 3–23. https://doi.org/10.1016/j.foostr.2013.06.001

Held, I. M., & Soden, B. J. (2000). Water vapor feedback and global warming. *Annual Review of Energy and the Environment*, *25*(1), 441–475. https://doi.org/10.1146/annurev.energy.25.1.441

Hodges, R. J., Buzby, J. C., & Bennett, B. (2011). Postharvest losses and waste in developed and less developed countries: Opportunities to improve resource use. *The Journal of Agricultural Science*, *149*(S1), 37–45. https://doi.org/10.1017/S0021859610000936

Hogan, D., & Schlenker, W. (2024). Empirical approaches to climate change impact quantification. In *Handbook of the economics of climate change* (Vol. 1, No. 1, pp. 53–111). North-Holland. https://doi.org/10.1016/bs.hesecc.2024.10.006

International Atomic Energy Agency. (2020). *Food systems and climate resilience technical meeting report*. https://www.iaea.org/sites/default/files/gc/gc65-5.pdf

Intergovernmental Panel on Climate Change. (2018). *Global warming of 1.5°C*. https://www.scirp.org/reference/referencespapers?referenceid=2956560

Intergovernmental Panel on Climate Change. (2022). *Climate change 2022: Impacts, adaptation and vulnerability*. Cambridge University Press. https://www.ipcc.ch/report/ar6/wg2/

Ivanov, D., & Dolgui, A. (2020). Viability of intertwined supply networks: Extending the supply chain resilience angles towards survivability. A position paper motivated by COVID-19 outbreak. *International Journal of Production Research*, *58*(10), 2904–2915. https://doi.org/10.1080/00207543.2020.1750727

Karl, T. R., & Trenberth, K. E. (2003). Modern global climate change. *Science*, *302*(5651), 1719–1723. https://doi.org/10.1126/science.1090228

Katusiime, J., & Schütt, B. (2020). Integrated water resources management approaches to improve water resources governance. *Water*, *12*(12), 3424. https://doi.org/10.3390/w12123424

Kiehl, J. T., & Trenberth, K. E. (1997). Earth's annual global mean energy budget. *Bulletin of the American Meteorological Society*, *78*(2), 197–208. https://doi.org/10.1175/1520-0477(1997)078<0197:EAGMEB>2.0.CO;2

Knox, J., Hess, T., Daccache, A., & Wheeler, T. (2012). Climate change impacts on crop productivity in Africa and South Asia. *Environmental Research Letters*, *7*(3), 034032. https://doi.org/10.1088/1748-9326/7/3/034032

Knychala, M. M., Boing, L. A., Ienczak, J. L., Trichez, D., & Stambuk, B. U. (2024). Precision fermentation as an alternative to animal protein, a review. *Fermentation*, *10*(6), 315. https://doi.org/10.3390/fermentation10060315

Kumar, M., Prusty, M. R., Pandey, M. K., Singh, P. K., Bohra, A., Guo, B., & Varshney, R. K. (2023). Application of CRISPR/Cas9-mediated gene editing for abiotic stress management in crop plants. *Frontiers in Plant Science*, *14*, 1157678. https://doi.org/10.3389/fpls.2023.1157678

Lv, X., Wu, Y., Gong, M., Deng, J., Gu, Y., Liu, Y., ... Chen, J. (2021). Synthetic biology for future food: Research progress and future directions. *Future Foods*, *3*, 100025. https://doi.org/10.1016/j.fufo.2021.100025

Machell, J., Prior, K., Allan, R., & Andresen, J. M. (2015). The water energy food nexus–challenges and emerging solutions. *Environmental Science: Water Research & Technology*, *1*(1), 15–16. https://doi.org/10.1039/C4EW90001D

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Marx, W., Haunschild, R., & Bornmann, L. (2021). Heat waves: A hot topic in climate change research. *Theoretical and Applied Climatology*, *146*(1), 781–800. https://doi.org/10.1007/s00704-021-03758-y

Matías, J., Rodríguez, M. J., Carrillo-Vico, A., Casals, J., Fondevilla, S., Haros, C. M., ... Reguera, M. (2024). From "farm to fork": Exploring the potential of nutrient-rich and stress-resilient emergent crops for sustainable and healthy food in the Mediterranean region in the face of climate change challenges. *Plants*, *13*(14), 1914. https://doi.org/10.3390/plants13141914

McMillen, H., Ticktin, T., & Springer, H. K. (2017). The future is behind us: Traditional ecological knowledge and resilience over time on Hawai'i Island. *Regional Environmental Change*, *17*(2), 579–592. https://doi.org/10.1007/s10113-016-1032-1

Mohanavelu, A., Naganna, S. R., & Al-Ansari, N. (2021). Irrigation induced salinity and sodicity hazards on soil and groundwater: An overview of its causes, impacts and mitigation strategies. *Agriculture*, *11*(10), 983. https://doi.org/10.3390/agriculture11100983

Nascimento, A. P. S., & Barros, A. N. (2025). Sustainable innovations in food microbiology: Fermentation, biocontrol, and functional foods. *Foods*, *14*(13), 2320. https://doi.org/10.3390/foods14132320

Osazuwa, O. M. C., Oghogho, M. Y., Mboto, A. A., Onogwu, G. P., & Gogogwute, O. (2025). Climate change and civil conflict in Africa: Understanding the interconnections. *American Journal of Political Science Law and Criminology*, *7*(5), 158–174. https://doi.org/10.37547/tajpslc/Volume07Issue05-18

Parfitt, J., Barthel, M., & Macnaughton, S. (2010). Food waste within food supply chains: Quantification and potential for change to 2050. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *365*(1554), 3065–3081. https://doi.org/10.1098/rstb.2010.0126

Pinchoff, J., Austrian, K., Rajshekhar, N., Abuya, T., Kangwana, B., Ochako, R., ... Ngo, T. D. (2021). Gendered economic, social and health effects of the COVID-19 pandemic and mitigation policies in Kenya: Evidence from a prospective cohort survey in Nairobi informal settlements. *BMJ Open*, *11*(3), e042749. https://doi.org/10.1136/bmjopen-2020-042749

Plank, C., Haas, W., Schreuer, A., Irshaid, J., Barben, D., & Görg, C. (2021). Climate policy integration viewed through the stakeholders' eyes: A co-production of knowledge in social-ecological transformation research. *Environmental Policy and Governance*, *31*(5), 387–399. https://doi.org/10.1002/eet.1938

Rai, G. K., Khanday, D. M., Kumar, P., Magotra, I., Choudhary, S. M., Kosser, R., Kalunke, R., Giordano, M., Corrado, G., Rouphael, Y., & Pandey, S. (2023). Enhancing crop resilience to drought stress through CRISPR-Cas9 genome editing. *Plants*, *12*(12), 2306. https://doi.org/10.3390/plants12122306

Rathore, S., Goyal, R., Jangir, B., Ummenhofer, C. C., Feng, M., & Mishra, M. (2022). Interactions between a marine heatwave and Tropical Cyclone Amphan in the Bay of Bengal in 2020. *Frontiers in Climate*, *4*, 861477. https://doi.org/10.3389/fclim.2022.861477

Rokhideh, M., Fearnley, C., & Budimir, M. (2025). Multi-hazard early warning systems in the Sendai framework for disaster risk reduction: Achievements, gaps, and future directions. *International Journal of Disaster Risk Science*, *16*(1), 103–116. https://doi.org/10.1007/s13753-025-00622-9

Sagar, A., Rathore, P., Ramteke, P. W., Ramakrishna, W., Reddy, M. S., & Pecoraro, L. (2021). Plant growth promoting rhizobacteria, arbuscular mycorrhizal fungi and their synergistic interactions to counteract the negative effects of saline soil on agriculture: Key macromolecules and mechanisms. *Microorganisms*, *9*(7), 1491. https://doi.org/10.3390/microorganisms9071491

Sehrawat, A., Sindhu, S. S., & Glick, B. R. (2021). Hydrogen cyanide production by soil bacteria: Biological control of pests and promotion of plant growth in sustainable agriculture. *Pedosphere*, *32*(1), 15–38. https://doi.org/10.1016/S1002-0160(21)60058-9

Sharma, A., Jain, A., Gupta, P., & Chowdary, V. (2021). Machine learning applications for precision agriculture: A comprehensive review. *IEEE Access*, *9*, 4843–4873. https://doi.org/10.1109/ACCESS.2020.3048415

Siddiqui, S. A., Erol, Z., Rugji, J., Taşçı, F., Kahraman, H. A., Toppi, V., Musa, L., Di Giacinto, G., Bahmid, N. A., Mehdizadeh, M., & Castro-Muñoz, R. (2023). An overview of fermentation in the food industry: Looking back from a new perspective. *Bioresources and Bioprocessing*, *10*, 85. https://doi.org/10.1186/s40643-023-00702-y

Starr, K. N. P., McDonald, S. R., & Bales, C. W. (2015). Nutritional vulnerability in older adults: A continuum of concerns. *Current Nutrition Reports*, *4*(2), 176–184. https://doi.org/10.1007/s13668-015-0118-6

Stavi, I., Thevs, N., & Priori, S. (2021). Soil salinity and sodicity in drylands: A review of causes, effects, monitoring, and restoration measures. *Frontiers in Environmental Science*, *9*, 712831. https://doi.org/10.3389/fenvs.2021.712831

Swapan, C., Mainak, B., Deewa, B., & Tanmoy, M. (2023). Natural pesticides for pest control in agricultural crops: An alternative and eco-friendly method. *Plant Science Today*. https://doi.org/10.14719/pst.2547

Termeer, C. J., Dewulf, A., & Biesbroek, G. R. (2017). Transformational change: Governance interventions for climate change adaptation from a continuous change perspective. *Journal of Environmental Planning and Management*, *60*(4), 558–576. https://doi.org/10.1080/09640568.2016.1168288

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Tirado, M. C., Clarke, R., Jaykus, L. A., McQuatters-Gollop, A., & Frank, J. M. (2010). Climate change and food safety: A review. *Food Research International*, *43*(7), 1745–1765. https://doi.org/10.1016/j.foodres.2010.07.003

Trenberth, K. E., Fasullo, J., & Smith, L. (2005). Trends and variability in column-integrated atmospheric water vapor. *Climate Dynamics*, *24*(7), 741–758. https://doi.org/10.1007/s00382-005-0017-4

Ullrich, P. A., Xu, Z., Rhoades, A. M., Dettinger, M. D., Mount, J. F., Jones, A. D., & Vahmani, P. (2018). California's drought of the future: A midcentury recreation of the exceptional conditions of 2012–2017. *Earth's Future*, *6*(11), 1568–1587. https://doi.org/10.1029/2018EF001007

Verma, M. L., Kumar, A., Chintagunta, A. D., Samudrala, P. J. K., Bardin, M., & Lichtfouse, E. (2024). Microbial production of biopesticides for sustainable agriculture. *Sustainability*, *16*(17), 7496. https://doi.org/10.3390/su16177496

Vermelho, A. B., Cardoso, V. D. S., Domingos, L. T. S., Akamine, I. T., Amenu, B., Osei, B. K., & Neves Junior, A. (2025). Advancements in microbial applications for sustainable food production. *Foods*, *14*(19), 3427. https://doi.org/10.3390/foods14193427

Wang, Y., Zafar, N., Ali, Q., Manghwar, H., Wang, G., Yu, L., Ding, X., Ding, F., Hong, N., & Wang, G. (2022). CRISPR/Cas genome editing technologies for plant improvement against biotic and abiotic stresses: Advances, limitations, and future perspectives. *Cells*, *11*(23), 3928. https://doi.org/10.3390/cells11233928

Waseem, H. B., & Rana, I. A. (2023). Floods in Pakistan: A state-of-the-art review. *Natural Hazards Research*, *3*(3), 359–373. https://doi.org/10.1016/j.nhres.2023.06.005

Wheeler, T., & von Braun, J. (2013). Climate change impacts on global food security. *Science*, *341*(6145), 508–513. https://doi.org/10.1126/science.1239402

Wiers, R. W., Marroun, H. E., Bockting, C., & Krugers, H. (2025). Debate: Urban versus rural environments—Which is better for mental health? The one good thing about a small town. *Child and Adolescent Mental Health*, *30*(2), 189–191. https://doi.org/10.1111/camh.12771

Wilhite, D. A. (2000). *Drought: A global assessment* (Vols. 1–2). Routledge. https://www.scirp.org/reference/referencespapers?referenceid=202287

World Bank. (2021). *Food security and climate vulnerability report*. https://www.worldbank.org/en/topic/agriculture/brief/food-security-update

World Health Organization. (2021). *Malnutrition fact sheets*. https://www.who.int/news-room/fact-sheets/detail/malnutrition

Yadav, R. K., Tripathi, M. K., Tiwari, S., Tripathi, N., Asati, R., Chauhan, S., Tiwari, P. N., & Payasi, D. K. (2023). Genome editing and improvement of abiotic stress tolerance in crop plants. *Life*, *13*(7), 1456. https://doi.org/10.3390/life13071456

Zhang, Y., Jing, M., Lyu, L., Nie, L., Xu, X., Sun, R., ... Chu, H. (2026). Principles for rigorous design and application of synthetic microbial communities. *Advanced Science*, *13*(10), e14750. https://doi.org/10.1002/advs.202514750

Zurek, M., Ingram, J., Sanderson Bellamy, A., Goold, C., Lyon, C., Alexander, P., ... Withers, P. J. (2022). Food system resilience: Concepts, issues, and challenges. *Annual Review of Environment and Resources*, *47*(1), 511–534. https://doi.org/10.1146/annurev-environ-112320-050744

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