Assessing the vulnerability of food supply chains to climate change-induced disruptions

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Review

Assessing the vulnerability of food supply chains to climate change-induced disruptions

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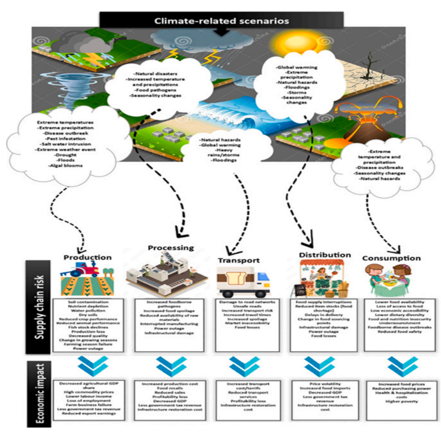
HIGHLIGHTS

- Climate change's impact on food supply chain explored
- 1526 publications analysed, 67 selected for review
- Findings highlight vulnerability due to climate change.
- Emphasis on need for research across food chain
- Neglecting socio-economic consequences risks supply chain failure

GRAPHICAL ABSTRACT



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ABSTRACT

Climate change is one of the most significant challenges worldwide. There is strong evidence from research that climate change will impact several food chain-related elements such as agricultural output, incomes, prices, food access, food quality, and food safety. This scoping review seeks to outline the state of knowledge of the food supply chain's vulnerability to climate change and to identify existing literature that may guide future research, policy, and decision-making aimed at enhancing the resilience of the food supply chain. A total of 1526 publications were identified using the SCOPUS database, of which 67 were selected for the present study. The vulnerability assessment methods as well as the adaptation and resilience measures that have been employed to alleviate the impact of climate change in the food supply chain were discussed. The results revealed a growing number of publications providing evidence of the weakening of the food supply chain due to climate change and extreme weather events. Our assessment demonstrated the need to broaden research into the entire food supply chain and various forms of climatic variability because most studies have concentrated on the relationships between climatic fluctuations (especially extreme rainfall, temperatures, and drought) and production. A lack of

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knowledge about the effects of climate change on the food supply chain and the underlying socio-economic consequences could result in underperformance or failure of the food supply chain.

1. Introduction

Crops, livestock, and fisheries all contribute significantly to the global economy and the well-being of populations, but their production and supply are highly climate-sensitive (Godde et al., 2021). When external factors and disturbances such as climate change affect the food system's components, including food supply, access, and consumption, food security is threatened (Gomez-Zavaglia et al., 2020). Climate change is unquestionably one of the greatest challenges worldwide, influencing the environment, society, and commercial operations (Ghadge et al., 2020). The extensive interrelatedness of supply networks, economic globalization, and climate change places a double burden on society because, although there are many uncertainties around climate change, it is evident that both the effects of climate change and globalization will have an influence on multiple regions, industries, ecosystems, and social groups (O'Brien and Leichenko, 2000). All aspects of the food supply chain, including production, processing, transport, wholesale, retailing, and consumption (Fig. 1), are susceptible to various environmental changes and natural disruptions. Climate change has effects that extend beyond local supply chains and are felt along longer supply networks (Davis et al., 2021). The food supply chain is affected by a range of climate change-associated events. These events include increased levels of tropospheric ozone (O_3) and atmospheric carbon dioxide (eCO_2), rising sea levels, changes in seasons and precipitation, fluctuations in mean temperature, and an increase in the frequency and intensity of extreme weather events such as heat waves, floods, storms, wildfires, and droughts (Godde et al., 2021; Ghadge et al., 2020).

The Intergovernmental Panel on Climate Change (IPCC) forecasted alterations in areas suitable for food production, freshwater, and biodiversity (Intergovernmental Panel on Climate Change Climate Change and Land, 2022). Anthropogenic activities impact over 70 % of the world's ice-free land surface (Arneth et al., 2020). Around 50 % decline in yields of rain-fed agriculture systems was predicted across Africa, with an average temperature increase between 1 and 3 degrees Celsius (Gomez-Zavaglia et al., 2020). Climate change will make it more difficult to achieve food security because of the anticipated adverse effects on agriculture, especially in developing, tropical and subtropical nations where agricultural yields are expected to drop drastically, consequently impacting food prices and the economy (Armah et al., 2011). The prices of the most significant crops, such as rice, wheat, corn, and soy, will increase due to climate change. Higher feed prices will result in higher meat prices, which will reduce the consumption of meat and cereals substantially (Nelson et al., 2023). This increase in food prices immediately impacts the majority of urban consumers because they depend primarily on food purchases for their nourishment (Chari and Ngcamu, 2022). Fisheries and aquaculture play a significant role as an animal protein source, providing 20 % of the average animal protein intake for around 3.2 billion people (Das et al., 2020). Changes to physiology, phenology, distribution patterns, and ecology are just a few examples of the adaptations that marine organisms may exhibit in response to climate change. These biological adaptations might cause deteriorations in the quality of the marine ecosystem and will ultimately influence the distribution and productivity of marine fisheries (Lam et al., 2012).

The predicted alterations in global climate provide opportunities and challenges for society and the economy. Designing effective strategies to solve climate change issues represents a vast opportunity (Allison et al., 2009). A better comprehension of the climate change-related elements influencing the food supply chain's susceptibility is vital to lower the risks of food and nutrition insecurity brought by food price instability and food shortages (Hecht et al., 2019; Hoffmann and Schöpflin, 2022). This knowledge will assist in the implementation of suitable measures and design of resilience policies to combat the profound effects of long-term climate change, to reduce the rate of climate change and build robust supply chains (Davis et al., 2021; Hecht et al., 2019; Hoffmann and Schöpflin, 2022).

The present paper evaluates the potential vulnerability issues related

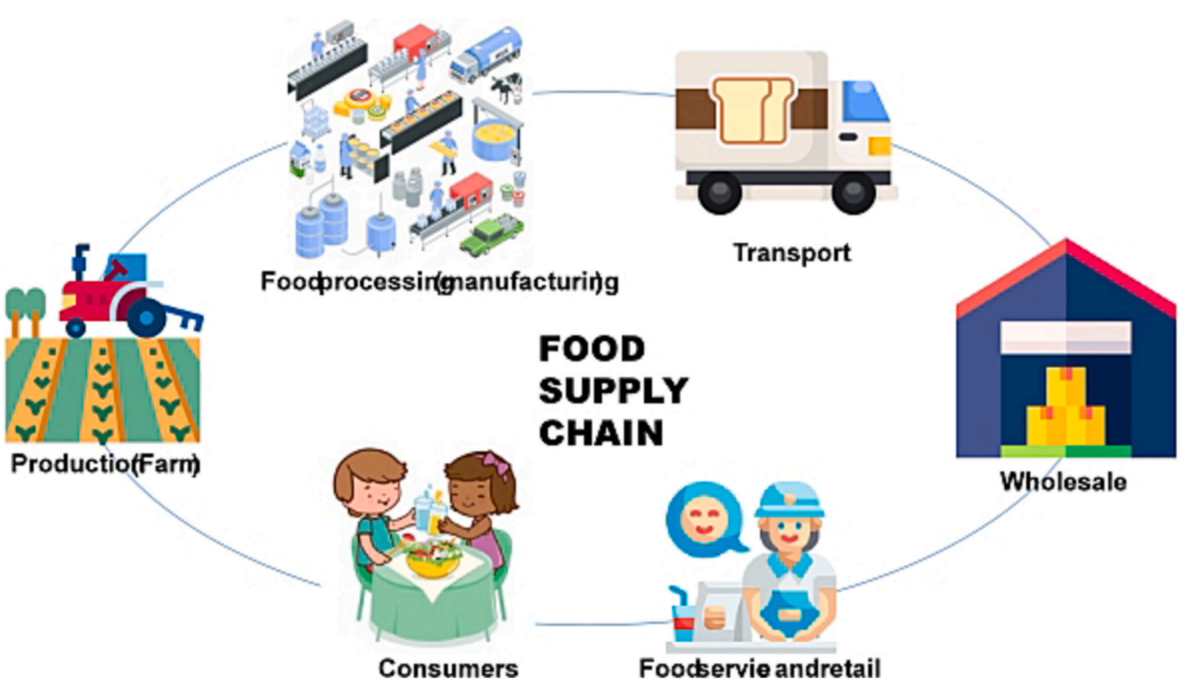

Fig. 1. Illustration of the food supply chain.

to the transformative effects of climate change in the food supply chain, following a scoping review of the available literature. The results and discussion of this study summarize findings/current knowledge on the topic, while emphasizing how climate change challenges the global food supply chain's resilience and food security. The approaches to measure vulnerability and the strategies to mitigate and/or adapt to climate change effects are described. Insights that can provide directions for future research and inform policy discussions are discussed.

This review seeks to shed light on the key climate change-induced disruptions that can affect food supply chains, the factors that contribute to the vulnerability of food supply chains, the methods used to assess the vulnerability of the food supply chain, the different strategies used for enhancing the resilience of food supply chains to climate change-induced disruptions, and the implications of the vulnerability of food supply chains to climate change-induced disruptions for food security, policy, and practice.

2. Methodology

2.1. Database search and identification of studies

A scoping review of the academic literature was conducted to achieve the study's goals. Scoping reviews effectively synthesise research evidence, map the literature, identify knowledge gaps, and provide an overview of evidence, concepts, or research in a specific field. The findings of scoping reviews can indicate areas where additional research may be necessary and guide the development of future research (Pollock et al., 2021; Munn et al., 2022).

For this scoping study, the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) statement for scoping reviews served as a methodological guide. A thorough search of the SCOPUS bibliographic databases was performed using the main keywords derived from the research topic. SCOPUS was used to conduct this scoping review because it is the world's largest abstract and citation database of peer-reviewed literature (this includes journals, books, and conference proceedings) (Geng et al., 2017). The search process involved two search string boxes with main keywords in all fields as follows; a) Search string box 1: 'Food supply chain', 'Climate Change', 'Vulnerability' and 'Disruptions', b) Search string box 2: 'Food supply', 'Climate Change', 'Vulnerability' and 'Disruptions'. The key search terms were combined with additional keywords in the two search string boxes to refine the search (Box 1 and Box 2).

The table below (Table 1) provides the inclusion and exclusion criteria for the study.

Table 1
Inclusion and exclusion criteria.

Inclusion Criteria	Exclusion Criteria
-Articles written in English	- Type of publications: Books, conference papers, proceeding papers
- Selected period: January 2010 to March 2023	-No access to full text
- Peer-reviewed publications	- Articles that do NOT include relevant information on the effect of climate-related events on the food supply chain (i.e. production, processing, distribution, consumption)
- Type of publications: original articles, reviews, scoping reviews, systematic reviews, meta-analyses, narrative reviews	-Articles focusing on plants, animals, and derived products that are not in the food supply chain, meaning they are not used for consumption by humans or animals raised for food.
- Publications primarily focused on the food system or stages of the food supply chain with the aim to analyse, investigate or demonstrate the relationship between climate-related occurrences, productivity, and the functioning of food chain stages	

2.2. Screening and selection of publications

In March 2023, initial searches were conducted, and the 1526 identified records were imported into Zotero software. Duplicates were deleted, and the screening process of the retrieved papers was performed in two phases. The first phase involved screening based on titles, keywords, and abstracts. The second phase involved assessing the eligibility of the retained papers through full-text consultations. The PRISMA flow diagram summarizing the selection is provided in Fig. 2.

Firstly, the titles and abstracts were screened for eligibility. Following the initial review of the titles and abstracts, 180 papers were chosen while the remaining articles were excluded because they did not match inclusion criteria and/or did not align with our study objectives. Following that, the authors meticulously reviewed the complete text of all possibly relevant articles in the second selection phase to confirm whether or not they should be included. In case of doubts/disagreement, discussions were carried out to reach a decision on including or excluding publications. Finally, 67 publications were selected for reasons consistent with the exclusion/inclusion criteria and study objectives.

3. Results

3.1. Frequency of publication

The database search revealed that the published research in this area has recently increased. Among the selected publications, there was a higher number of papers published in 2022. The number of papers published per year can be seen in Fig. 3.

3.2. Content analysis of selected publications

In this section, the composition of each of the selected publications was described. The following Table 2 categorizes the articles based on title, year of publication, supply chain stage (1. Production, 2. Processing, 3. Distribution, 4. Consumption), food category (1. Fruits & vegetables 2. Grains, cereals, nuts, and seeds 3. Meat and poultry (including eggs) 4. Dairy 5. Fish and seafood 6. Roots and tubers 7. Beverages 8. Fat (oils and spreads) 9. Herbs and spices), main objective of the study, and relevant findings. The categorization of supply chain stages in Table 2 is described as follows: production includes primary production activities like crop & animal production as well as post-harvest activities that do not significantly alter farmed products, processing involves transforming raw materials (e.g. crops, livestock, fisheries) to semi-finished/finished products, distribution includes wholesale, retail & transport, and consumption includes human consumption (e.g. household consumption).

According to Table 2, most of the publications studied primary production. The processing stage had the fewest number of articles. Also, multiple stages of the food supply chain (e.g. distribution and production or production and distribution) were discussed in some articles. While some publications addressed the climate change effect on the food supply chain in general, this includes papers studying food systems (such papers were coded as 'whole food chain'). Fig. 4 shows the percentage of publication according to their target supply chain component.

In terms of food categories, some studies did not address any specific food category. It was observed that, the two most studied food categories were Grains, cereals, nuts, and seeds followed by fish and seafood. Fig. 5 illustrates the number of studies per food category.

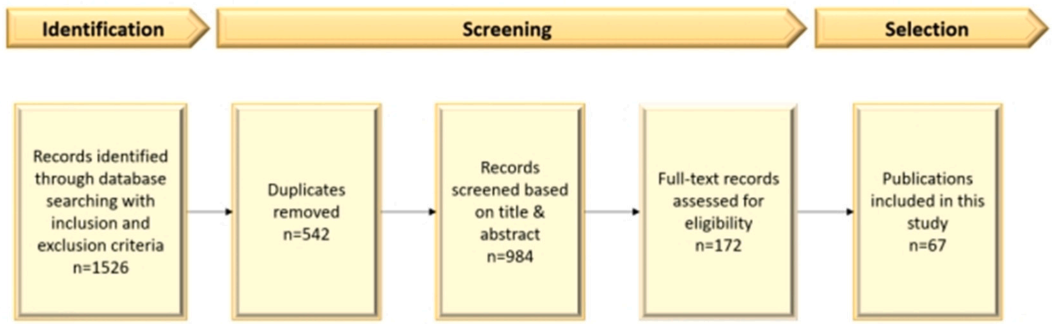

Fig. 2. Study flow diagram.

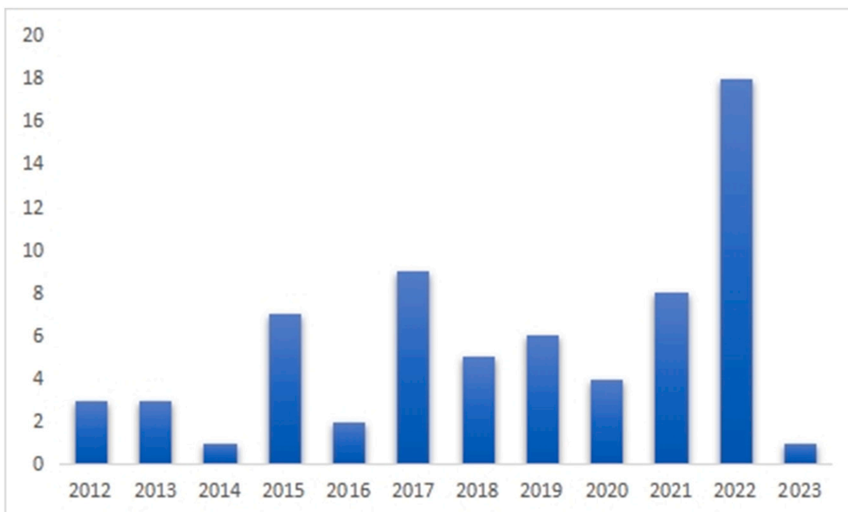

Fig. 3. Number of publications per year (limited to the articles included in the study, $n = 67$).

3.3. *Assessment of vulnerability of food supply chains to climate change-induced disruptions*

(i) Key climate change-induced disruptions that can affect food supply chains

Variations in climatic conditions can affect different food categories and/or component of the food supply chain. Failures or disruptions can occur at the primary production, processing, wholesale, distribution, retail, and food donation/assistance levels (Lebot, 2013). Primary production (i.e. crop & grain production, livestock rearing, seafood and poultry farming) is the element of the food chain that is anticipated to face higher challenges due to climate change, which will have an impact on industries that use agricultural products as raw materials (Chari and Ngcamu, 2017). The best-known impact of climate change-associated disruptions on agricultural systems is reduced productivity that negatively affects the food supply (Tramblay et al., 2020). Climate change impacts further down the food supply chain might generally be perceived as being indirect impacts that are consequences of disruptions suffered by primary production (Myers et al., 2017).

Elevated temperatures and droughts are two major environmental shocks that negatively affect global food production and yield (Myers et al., 2017). Heat waves have been linked to farmed product destruction, hard soils, poor yields, and non-pollination. Drought risk will increase due to falling precipitation, which will contribute to output losses in the agrifood sector and related industries (Senapati et al., 2019; Lin et al., 2020). Due to drought and desertification, 12 million hectares of land are degraded annually (Emadodin et al., 2019). The most noticeable effects are seen in African, Asian, and Latin American countries with higher vulnerability to soil degradation, but it is also becoming more prevalent in other parts of the world, particularly Eastern European countries and the Mediterranean region (Greece, Portugal, Spain, Croatia, Italy, Cyprus, France, Malta, Albania, Bosnia and Herzegovina, Slovenia, and Turkey) (Daszkiewicz, 2022).

Agricultural food production can be disrupted as a result of resource contamination (e.g. soil and water contamination (Ahmed et al., 2016) and animal feed contamination (Xu et al., 2022)), growing season failure associated with lower production due to pests, disease outbreaks (Singh et al., 2023; Anyamba et al., 2009) or adverse weather phenomena, and farm business failure (Kingwell and Payne, 2020). Resources such as soil, water, fuel, seeds, animal feed, fertilizers, pesticides, and pollinator distribution are inputs that are crucial to food production based on the food produced and the techniques used during production. These inputs are susceptible to a number of interrelated environmental shocks, such as climate change, water scarcity, and biodiversity loss (Chodur et al., 2018). Crop pollination is impacted by a decrease in the availability of appropriate habitat, which may result in territory reductions, shifts in habitat, pollinator loss and incompatibility between the pollinator and the cultivated crop. For example, a sharp loss in five tomato-pollinating bee species is expected by the year 2100 in Brazil (Elias et al., 2017). Leonhardt et al. (2013) reported a reduction in the vulnerability to pollination instability from warmer to colder EU nations. Hence warmer southern European regions are more at-risk to pollinator loss than northern regions because food production in countries located in the South (particularly Malta and Italy) are highly dependent on pollination services (Leonhardt et al., 2013). A decline in pollinator populations

Table 2
Categorization of the articles included in the scoping review.

#	Title	Year	Supply Chain Stage	Food Category	Study objective	Relevant/key findings	Reference
1	Review of climate change impacts on marine aquaculture in the UK and Ireland	2012	Production	Fish & seafood	Assesses the opportunities and dangers of climate change for aquaculture in Ireland and the UK, focusing on the most farmed aquatic species, blue mussels and Atlantic salmon	Infrastructure (like salmon cages) is at danger due to changes in storm frequency and intensity. Changes in rainfall patterns can trigger harmful algal blooms, affecting bivalve farming. The shift in shoreline morphology due to sea level rise, can reduce the size of the area suitable for production. Ocean acidification may interfere with early developmental stages of shellfish. Diseases, parasites, and pathogens may become more virulent, translocate, or emerge as a result of climate change. Rising temperatures might favour the farming of warm-water species in the UK and Ireland.	(Callaway et al., 2012)
2	Yield stability for cereals in a changing climate	2012	Production	Grains, cereals, nuts, and seeds	Discusses the effect of abiotic stressors on reproductive development and productivity in cereals, focusing on temperature stresses (cold/frost and heat), and extremes of water availability (drought and waterlogging).	Improving cereal productivity should not only target increasing yield, but also enhanced tolerance to abiotic stresses for grain yield to be maintained under environmental constraints associated with climate change. The development of enhanced abiotic stress tolerance characteristics in cereals is impeded by a lack of accurate screening techniques, the availability of adequate germplasm, and a lack of understanding of the physiological and molecular foundations of abiotic stress tolerance traits.	(Powell et al., 2012)
3	Challenges for drought mitigation in Africa: The potential use of geospatial data and drought information systems	2012	Production	NA	To show how geospatial technology-based drought information systems, employing both static and real-time data, might enhance drought mitigation in Africa.	It is essential to promote drought preparedness and mitigation at the national and regional levels in order to manage drought risk using a crisis-response-based reactive approach.	(Vicente-Serrano et al., 2012)
4	Coping with insularity: The need for crop genetic improvement to strengthen adaptation to climatic change and food security in the Pacific	2013	Production	Fruits & vegetables Roots & tubers	Reviews the adaptation potential of Pacific food crops to climate change.	In the Pacific area, there are few attempts to increase food self-sufficiency and resilience. The creation of breeding initiatives with the goal of enlarging the genetic bases of the main food crops ought to be prioritised.	(Lebot, 2013)
5	Economic gain, stability of pollination and bee diversity decrease from southern to northern Europe	2013	Production	NA	To calculate economic gains attributed to pollination and their contribution to the total value of crop production (vulnerability) from 1991 to 2009 for countries in the European Union.	Dependence on insect pollination rose from the north to the south, but there was a lower variability in the economic benefit from insect pollination, implying that the Mediterranean nations had more consistent yields of crops dependent on pollinators and more dependable pollination services.	(Leonhardt et al., 2013)
6	Global climate change, threat to food safety and poverty	2013	Consumption	NA	Examines the impact of climate change on food security, farmers' activities, and poverty, focusing on developing countries.	Negative impacts of climate change affect food security and production. This increases hunger and poverty. A holistic application of sustainable development which also applies to agriculture should be pursued to have better food access and sustainable livelihoods.	(Odeku, 2013)
7	Climate change risks and adaptation options across Australian seafood supply chains – A preliminary assessment	2014	Production	Fish & seafood	To examine potential impacts of climate change across seafood supply chains	Climate change consequences are well recognized at the harvest stage, and there is evidence of potential repercussions and supply chain disturbance. However, there is no significant drive for change further in the chain. Holistic adaptation planning along the supply chain is required, supported by customized information and policy for the	(Fleming et al., 2014)

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Table 2 (*continued*)

#	Title	Year	Supply Chain Stage	Food Category	Study objective	Relevant/key findings	Reference
						catch, processing and distribution, and marketing stages.	
8	The role of international trade in managing food security risks from climate change	2015	Distribution & Consumption	NA	Investigates the increasing inter-annual supply-side volatility, adaptations to this volatility as well as the role of international commerce in reducing the negative effects of volatility on food security.	The changing climate will lead to greater food price volatility. The food price consequences of climatic hazards are likely to hit hardest people already vulnerable to poverty and hunger. Improved market integration and the elimination of trade bottlenecks can help to reduce food price volatility caused by climatic extremes.	(Baldos and Hertel, 2015)
9	Resilience to global food supply catastrophes	2015	Whole food chain	NA	This study addresses approaches for enhancing food supply resilience to climate-related hazards.	Food stockpiles, agriculture, and foods derived from other (non-sunlight) energy sources such as biomass and fossil fuels are mentioned as three solutions for enhancing food supply resilience.	(Baum et al., 2015)
10	Toward strategies to adapt to pressures on safety of fresh produce due to climate change	2015	Production	NA	The study's main goal was to provide insights from a systems viewpoint regarding which climate-induced incidents puts pressure on safety of fresh produce and what primary production response measures can be employed.	The researchers emphasized the necessity to improve pesticide management, irrigation techniques, pest control, water treatment and quality monitoring, personal hygiene specifications, and (cold) storage management to ensure food safety in a changing climate	(Kirezieva et al., 2015)
11	The vulnerability of the US food system to climate change	2015	Production	NA	Explores the climate change vulnerability of the food supply in the United States.	Lower water resources, warmer winters, and more altering spring weather are especially disruptive to vegetable and fruit cultivation in the Northwest and Southwest. Greater weather unpredictability, such as warmer winters, heat waves, and scorching summer evenings, as well as flooding induced by more frequent heavy rains puts grain production in the Midwest and Great Plains at risk. The high volume of cattle, pig, and poultry farming in confined animal feeding operations in the southern Great Plains and Southeast is especially vulnerable to a higher incidence and severity of extreme weather, as well as interrupted feed, water, and power supplies.	(Lengnick, 2015)
12	Potential impacts of climate change on agriculture and food safety within the island of Ireland	2015	Production	NA	This article discusses some of the major climate change-related processes that are anticipated to have an impact on food safety and security, with a focus on the island of Ireland.	Significant changes in local ecosystems are expected. There might be new pest species arising, such as invading insects, weeds, or fungus. Due to the novel nature of the pests and farmers' lack of experience with controlling them, through pesticides or other techniques, management responses may cause food safety issues. Mycotoxins may pose a greater threat if the environment becomes more conducive to the spread of diseases.	(Lennon, 2015)
13	Double Exposure to Climate Change and Globalization in a Peruvian Highland Community	2015	Production	NA	To examine the exposure and adaptations of small-scale farmers in Langui (Peru) using individual observations, interviews, & district-level data from the 1994 and 2012 Peruvian agricultural censuses.	Agriculture in Langui is experiencing several adjustments as people shift from growing traditional crops to planting improved species of grasses for dairy and livestock production.	(Lennox, 2015)
14	Post-disaster grain supply chain resilience with government aid	2015	Distribution	Grains, cereals, nuts, and seeds	To identify the best options for grain supply chain (GSC) contingency plan when grain processors encounter supply chain constraints due to natural catastrophes.	Extreme weather conditions and natural disasters hinder grain transportation, negatively influencing prices. When the government intervenes to sell unhusked rice in the market during agricultural recovery periods following disasters, processors and	(Yang and Xu, 2015)

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Table 2 (*continued*)

#	Title	Year	Supply Chain Stage	Food Category	Study objective	Relevant/key findings	Reference
						retailers have higher profits. As a result, government assistance can assist them in increasing revenues (or reducing losses) through recovery behaviour. Although government intervention is necessary to stabilize prices, it can only serve as a supplement to, not a replacement for, market mechanisms.	
15	Economic costs of reduced irrigation water availability in Uzbekistan (Central Asia)	2016	Production	NA	To examine the economic impacts of decreasing water supply in Uzbekistan, a nation that houses over 50 % of Central Asia's irrigated crop lands	An estimated 241,000–374,000 ha (6.3–9.7 %) of irrigated land could be abandoned due to a 10–20 % decrease in mean water supply for irrigation, which would result in 5.1–8.2 % job loss in the farming sector and 7.9–9.6 % job loss in the entire economy	(Bekchanov and Lamers, 2016)
16	Vulnerabilities to agricultural production shocks: An extreme, plausible scenario for assessment of risk for the insurance sector	2016	Production	Grains, cereals, nuts, and seeds	To study the potential implications of agricultural system disruptions through the generation of a multiple-crop production shock scenario due to climate extremes and biotic stresses.	The cumulative effects of the simulated agricultural production shocks (i.e. winter snows, drought, strong rains, etc.) result in worldwide crop output losses of 10 % for maize, 11 % for soy, 7 % for wheat, and 7 % for rice. As a result, rising commodity prices and commodity stock volatility, along with civil instability will arise, resulting in negative humanitarian implications and major financial losses worldwide.	(Lunt et al., 2016)
17	Environmental policies to protect pollinators: Attributes and actions needed to avert climate borne crisis of oil seed agriculture in Pakistan	2017	Production	Grains, cereals, nuts, and seeds	The article explores simple adaptations and prospective measures that might help lessen the impact of climate change on pollinator health and performance, thereby reviving Pakistan's oil seed production.	It is suggested that proactive steps be taken to solve reduced pollinator services; otherwise, the geographical area for oil seed crops may decline, resulting in a low market stability index. A suggested plan of action could record current pollinator and insect-pollinated flora characteristics, investigate the role of various drivers in causing such tendencies, examine the ecological and monetary impacts of these changes and possible mitigation procedures that can be implemented, and disseminate outcomes to a wide range of stakeholders.	(Burhan et al., 2017)
18	An assessment of the impact of disaster risks on dairy supply chain performance in Zimbabwe	2017	Production	Dairy	This study used a mixed-method approach including structured questionnaires, semi-structured interviews, and observations to explore the influence of disaster risks on the efficiency of Zimbabwe's dairy supply chains.	Natural disaster risks have had a detrimental effect on dairy supply chain since they have lowered productivity and hampered business growth. Droughts, veld fires, and extreme weather conditions were among the natural catastrophes that damaged pastures and overall milk supply. Many individuals lost their jobs, causing many families to face food insecurity.	(Chari and Ngcamu, 2017)
19	Climate change threatens pollination services in tomato crops in Brazil	2017	Production	Fruits & vegetables	Investigate the potential implications of climate change on the spatial distribution of 5 native bee species, as well as the potential effects of bee geographical shifts on the cultivation of tomatoes in Brazil.	Climate change is expected to have a detrimental influence on various species related with tomato production in Brazil by the year 2100.	(Elias et al., 2017)
20	Potential climate change impacts on citrus water requirement across major producing areas in the world	2017	Production	Fruits & vegetables	This study investigates the effects of projected climate change on citrus irrigation needs in important citrus producing regions such as Africa, Asia, Australia, the Mediterranean, and the Americas.	Future evapotranspiration and citrus irrigation requirements are expected to fall by up to 12 and 37 %, respectively, as CO_2 concentrations rise.	(Fares et al., 2017)

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Table 2 (*continued*)

#	Title	Year	Supply Chain Stage	Food Category	Study objective	Relevant/key findings	Reference
21	Shocks to fish production: Identification, trends, and consequences	2017	Production	Fish & seafood	This research applied a statistical shock detecting methodology to find shocks (including environmental shocks) in historical aquaculture and fisheries data from 1976 to 2011.	Shocks were most common in the Caribbean, Central America, Middle East, North Africa, and South America. Asia, Europe, and Africa experienced the biggest severity levels. Shocks were also more common in aquaculture systems than in capture operations.	(Gephart et al., 2017)
22	Projected climate change threatens pollinators and crop production in Brazil	2017	Production	Fruits & vegetable	A total of 95 pollinators of 13 crops were evaluated for their spatial distribution in relation to climate change, and their corresponding effects on crop productivity were determined.	By 2050, anticipated climate change will lower the probability of pollinator occurrence by about 0.13. Pollinator species will be lost in over 90 % of the municipalities studied, affecting the cultivation of crops such as tomato, persimmon, mandarin, and sunflower. Climate change may benefit several communities in northern Brazil since pollinators for some crops may increase.	(Giannini et al., 2017)
23	Exploring future scenarios for the global supply chain of tuna	2017	Production	Fish & Seafood	The goal was to provide a framework for simulating global scenarios of tuna fisheries, considering biological (climate change) and economic (changes in tuna demand and establishment of high seas protected areas) processes.	Relatively minor changes were observed in the global tuna supply chain. There is a chance that tuna habitat carrying capacity won't decline. The most significant effect of climate change on tuna fisheries is probably going to be on recruitment.	(Mullon et al., 2017)
24	Climate Change and Global Food Systems: Potential Impacts on Food Security and Undernutrition	2017	Production, distribution & consumption	NA	To review the potential effects of climate change on food distribution and production, as well as any resulting effects on food and nutrition security	There are a lot of unknowns when it comes to the extent to which the climate will undergo alterations, as well as to how plants, animals, and farm workers will respond and/or adapt to these changes. It is necessary to be ready for a wide range of potential outcomes, even though these uncertainties make it difficult to anticipate precise changes in future food production. Also, habitats that are already exposed to high temperatures and have the fewest resources for adaptability are often adversely affected by the changing climate.	(Myers et al., 2017)
25	Food network resilience against natural disasters: A conceptual framework	2017	Whole food chain	NA	To provide a comprehensive framework for enhancing the resilience of the food supply chain and assisting in understanding supply chain resilience	This analysis demonstrated that there is still a lot to learn about food supply chain in catastrophe scenarios. The authors noted the lack of available data on the performance and resilience of food supply systems in regions affected by natural catastrophes as well as the need for more studies on food supply chain resilience.	(Umar et al., 2017)
26	Assessing food system vulnerabilities: A fault tree modelling approach	2018	Whole food chain	NA	This paper describes a prototype version of a fault tree, that may be used in modelling to highlight fundamental and intermediate elements that might lead to food system failures.	Failures in the food supply chain can occur at the stages of production, processing, wholesale, distribution, retail, or food donation sources. Each of these levels is vulnerable to events caused by adverse weather, contamination, and insufficient resources.	(Chodur et al., 2018)
27	Vulnerability of juvenile hermit crabs to reduced seawater pH and shading	2018	Production	Fish & seafood	The authors evaluated how lower pH and shading affected growth, mortality, calcification, displacement behaviour from live predators, and other factors in juvenile hermit crabs.	Low pH and darkness had a significant effect on mortality. No difference in calcification was recorded in acidic environments.	(Ragagnin et al., 2018)
28	Resilience in agri-food supply chains: a critical analysis of the literature and synthesis of a novel framework	2018	Whole food chain	NA	To provide a unique framework for agri-food supply networks resilience by using a systematic literature review to determine which transdisciplinary features of resilience are applicable to agri-food supply chains.	Disruptions cannot be seen as an isolated event due to the complexity of the food supply chain phases and their sensitivity to external interference; as a result, resilience must focus on the capacity to sustain essential functions while	(Stone and Rahimifard, 2018)

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Table 2 (*continued*)

#	Title	Year	Supply Chain Stage	Food Category	Study objective	Relevant/key findings	Reference
						also adapting to changing circumstances.	
29	Decreases in global beer supply due to extreme drought and heat	2018	Processing & Distribution	Beverages	Assessed the vulnerability of beer supply to climate extremes (e.g. heat and drought)	Depending on the severity, extreme events may result in average barley yield losses of between 3 % and 17 % worldwide. Reduced supplies of barley result in proportionately bigger reductions in the amount of barley used for beer production, which eventually cause a drop beer consumption (e.g. 32 % fall in Argentina) and price hikes (e.g. 193 % rise in Ireland).	(Xie et al., 2018)
30	The impact of climate change on the food system in toronto	2018	Whole food chain	NA	To identify vulnerabilities of the food system in Toronto (Canada) to floods, heat waves and ice storms	Power outages caused by climate extremes are likely to have the biggest effects on food access & safety, while fuel and transportation network disruptions could greatly impact distribution.	(Zeuli et al., 2018)
31	Increasing risks of multiple breadbasket failure under 1.5 and 2 °C global warming	2019	Production	Grains, cereals, nuts, and seeds	This research estimates the hazards to agriculture in a world that is 1.5 and 2 °C warmer, by studying climate risks posed to wheat, soybeans and maize in global food-producing zones (US, Argentina, Brazil, China, India, and Australia)	Exceeding the 1.5 °C warming threatens global food security. The probabilities of multiple breadbasket failures rise considerably in maize, from 6 % to 40 % at 1.5 °C to 54 % at 2 °C temperature rise.	(Gaupp et al., 2019)
32	Revisiting Emergency Food Reserve Policy and Practice under Disaster and Extreme Climate Events	2019	Distribution & Consumption	NA	This study investigated Malaysian, Philippine, and Indonesian policies on emergency food supplies reserves.	Most decisionmakers consider that having sufficient emergency food stores may mitigate national food price volatility, shocks from catastrophes and climate change, and cushion trade disruptions caused by export prohibitions during disasters and emergencies associated with climate change.	(Lassa et al., 2019)
33	The climate change, food security and human health nexus in Canada: A framework to protect population health	2019	Whole food chain	NA	To demonstrate the intricate connection between the effects of climate change and the food system, as well as how this connection affects Canada's food security and public health.	Climate-related events in the food chain may have a detrimental influence on food security (a key determinant of health) and could have an indirect effect on human health. Climate change's physical effects on the food chain, particularly those influencing nutrition and foodborne infections, may also have an influence on human health.	(Schnitter and Berry, 2019)
34	Drought tolerance during reproductive development is important for increasing wheat yield potential under climate change in Europe	2019	Production	Grains, cereals, nuts, and seeds	To assess the potential yield advantages of drought tolerance in wheat ideotypes' developmental stages under climate change circumstances in Europe and to identify relevant cultivar characteristics for crop improvement.	Drought stress resistance during reproductive development is crucial for high yield features and production stability.	(Senapati et al., 2019)
35	Modelling food sourcing decisions under climate change: A data-driven approach	2019	Production & Distribution	Fruits & vegetables Grains, cereals, nuts, and seeds	To determine if businesses should adjust their sourcing options in light of environmental alterations and how such changes are anticipated to influence the appropriateness and risk of various locations for growing certain food items.	The investigation revealed that while certain areas are currently more conducive for growing certain crops, they may become less suitable in the future. Due to changes in the suitability of production areas, decisions about the procurement of common food products are likely to necessitate major alterations.	(Srinivasan et al., 2019)
36	Role of market agents in mitigating the climate change effects on food economy	2019	Distribution	Grains, cereals, nuts, and seeds	To evaluate the contribution of domestic markets and global trade in reducing the loss of agricultural production driven by climate change, using the case of barley.	Domestic and international market inefficiencies would result in a 3.5 % and 0.6 % increase in local supply deficits respectively, for importers of barley under the worst-case scenario of extreme events. Market integration policies can successfully serve as climate change adaptation strategies.	(Xie et al., 2019)

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#	Title	Year	Supply Chain Stage	Food Category	Study objective	Relevant/key findings	Reference
37	Assessment of household-level food-energy-water nexus vulnerability during disasters	2020	Consumption	NA	To study how socioeconomic variables and integrated infrastructure disruptions affect household susceptibility to disasters (e.g. hurricane Harvey).	A home's susceptibility to disruptions that inhibit access to food, water & energy depends on a variety of factors, including physical characteristics, the severity of disruptions, household preparation habits, social and demographic characteristics. This illustrates the idea that a household's risk and susceptibility to disasters are significantly influenced by the pre-disaster conditions of the community in which they reside.	(Dargin et al., 2020)
38	Supply chain management enablers, barriers and disruptions in the animal feed industry in the Western Cape Province of South Africa	2020	Production	Meat and poultry (including eggs) Dairy	This study examines the supply chain management-related contributors to development (enablers), impediments, and disruptions in the livestock business in South Africa's Western Cape Province.	The supply chain management disruptions in the animal feed business were primarily associated with economic factors, illnesses, natural disasters, and low customer loyalty.	(Gomera and Mafini, 2020)
39	Cross-Strait climate change and agricultural product loss	2020	Production & Distribution	NA	The purpose of this study is to assess the direct and indirect effects of natural disasters on Taiwanese and Mainland Chinese agricultural sector.	Agriculture, forestry, fisheries, wholesale, retail, animal feed industry, and inorganic fertilizer industry are highly affected by the value-added losses induced by natural disasters. Agriculture is the most affected by disasters, accounting for 94.6 % of total value-added losses in Taiwan. Losses caused by typhoon and heavy rain had the greatest effect on agriculture, with 83 % losses in Taiwan.	(Lin et al., 2020)
40	Challenges for drought assessment in the Mediterranean region under future climate scenarios	2020	Production	NA	This review aims to give a broad overview of the current challenges in estimating droughts and the consequences in the Mediterranean basin under climate change.	The Mediterranean area is under pressure from population growth and urbanization, which necessitates increased water supply to meet agricultural, industrial, and domestic needs and, as a result, great deal of strain is placed on the scarce and vulnerable water resources of the Southern and Eastern nations, in particular. The distribution and consumption of water will suffer because of the current circumstances, which are predicted to get worse due to climate change.	(Tramblay et al., 2020)
41	Cross-border climate vulnerabilities of the European Union to drought	2021	Production & Distribution	NA	The goal of this study is to assess the European Union 's cross-border climatic vulnerabilities by estimating the change in drought sensitivity under climate change for the years 2030, 2050, and 2085.	Due to climate change, more than 44 % of agricultural imports into the European Union (EU) will be extremely vulnerable to drought. Compared to current levels, the drought severity in the regions where imported products are produced will increase by 35 % in 2050. This is particularly true for goods coming from Turkey, India, Brazil, Indonesia, Vietnam, and Thailand. Also, future agricultural imports from Kenya, Uganda, Peru, Ecuador, Nigeria, and Russia will be less susceptible.	(Ercin et al., 2021)
42	How to Prevent and Cope with Coincidence of Risks to the Global Food System	2021	Whole food chain	NA	In this article, pressing issues that have the biggest effects on the world food system are reviewed.	Climate change remains the single most serious threat to food systems, exacerbating all others.	(Fan et al., 2021a)
43	Flooding Causes Dramatic Compositional Shifts and Depletion of Putative Beneficial Bacteria on the Spring Wheat Microbiota	2021	Production	Grains, cereals, nuts, and seeds	To investigate how flooding affects the spring wheat-microbiota complex	Flooding causes negative changes in the composition of wheat microbiota. Floods cause hydrological stress that is detrimental for crop fitness and growth.	(Francioli et al., 2021)

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#	Title	Year	Supply Chain Stage	Food Category	Study objective	Relevant/key findings	Reference
44	Overview of bee pollination and its economic value for crop production	2021	Whole food chain	NA	This study examined the resilience and vulnerability of the management of crisis in the food supply chain in Puerto Rico.	100 % of participants agreed that a complete system collapse would have a significant impact on their food business. After hurricane Maria several food supply chain stakeholders were unable to swiftly resume operations due to inadequate transportation systems, loss of telecommunications, electricity interruptions & lack of government intervention	(Orengo Serra and Sanchez-Jauregui, 2021)
45	Puerto Rican Farmers' Obstacles Toward Recovery and Adaptation Strategies After Hurricane Maria: A Mixed-Methods Approach to Understanding Adaptive Capacity	2021	Production	NA	This study evaluated the use of adaptation strategies by Puerto Rican farmers considering the challenges they encountered in recovering from 2017's Hurricane Maria.	Farmers who suffered a complete loss made the most effective adaptations and farmers with higher levels of education were inclined to employ more adaptation techniques, indicating a link between human capital and the ability to modify farming operations following total losses. Despite being devastating, natural disasters like Hurricane Maria present opportunities to foster transformation and resilience. But being able to seize such opportunities depends not only on each farmer's human capital and social networks, but also on the institutional organizations and infrastructure that are currently available for recovery.	(Rodríguez-Cruz et al., 2021)
46	The perfect storm: extreme weather events and speculation along cardamom commodity chains in Southwest China	2021	Whole food chain	Herbs & spices	This study investigates how stakeholders in the black cardamom supply chain were influenced by severe weather in Southwest China in 2016.	The opportunities, benefits, and risks linked with the extreme weather events were distributed among those currently engaged in the cardamom supply chain. These stakeholders were affected in varied ways, in ways that mirrored and sustained actors' pre-disaster power dynamics and distinctive powers in influencing the market, but not their previous potential to gain from the cardamom trade.	(Rousseau and Xu, 2021)
47	Economic impacts of climate-induced crop yield changes: evidence from agri-food industries in six countries	2021	Production	Grains, cereals, nuts, and seeds	This research examines the economic effects of eight temperature rise scenarios ranging from 1.5 to 4 degrees Celsius on rice and wheat harvests in China, India, Brazil, Egypt, Ghana, and Ethiopia.	Agricultural production changes associated with warming of up to 3.5 and 3.0 °C have slight advantages on GDP and welfare in China, respectively. This is because rising rice productivity are expected to reduce rice prices. However, when temperatures rise above these levels, the above events begin to reverse. Other nations are facing difficulties because of falling crop yields and rising prices for domestic and imported rice and wheat, with India and Ethiopia being particularly impacted.	(Wang et al., 2021)
48	Looking across diverse food system futures: Implications for climate change and the environment	2021	Whole food chain	NA	This document synthesizes the primary drivers of food system transformation, with a special emphasis on the consequences for environmental and climate change.	Adapting to the effects of climate change is critical to sustaining our ability to feed the world's rising population. However, it is not clear how much adaptation will be sufficient to mitigate the negative effects of changing climatic variables across nations and agroecological zones.	(Zurek et al., 2021)
49	Impact of floods on undernutrition among children under five years of age in low- and middle-income countries: a systematic review	2022	Consumption	NA	To present comprehensive information on the effects of floods on child malnutrition in South Asia (Bangladesh, India, Nepal, and Pakistan).	Stunting was the most prevalent form of undernutrition in flood-affected communities.	(Agabiirwe et al., 2022)

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#	Title	Year	Supply Chain Stage	Food Category	Study objective	Relevant/key findings	Reference
50	Multifaceted Social and Environmental Disruptions Impact on Smallholder Plantations' Resilience in Indonesia	2022	Production	Grains, cereals, nuts, and seeds Fat (oils and spreads)	To assess the resilience of 360 smallholder farmers to social and environmental shocks in six villages in Bengkulu (Indonesia)	Farmers that grow coffee are the most adaptive smallholders. More than half of the farmers are less resilient to disruptions. Farmers regarded climate change as the most significant disruptive phenomenon on their plantations in terms of environmental shocks.	(Andani et al., 2022)
51	Human induced fish declines in North America, how do agricultural pesticides compare to other drivers?	2022	Production	Fish and seafood	The goal is to examine and contrast the major factors leading to the reduction of freshwater fish populations in North America.	The main causes of past, current, and future decreases in freshwater fish populations in North America include habitat modification, dams, invaders, overfishing, and climate change.	(Brain and Prosser, 2022)
52	Assessing changes in food pantry access after extreme events	2022	Distribution	NA	The purpose of this paper is to describe how access to food pantries has changed in Harris County, Texas after flooding incidents.	After floods, the majority of locals are able to access the current food pantry locations and the distance to the food pantries only slightly increase. Nevertheless, flooding tends to limit food pantry access for hundreds of thousands of residents, particularly in regions with a high chance of food insecurity and many low-income families.	(Casellas Connors et al., 2022)
53	Food Production in the Context of Global Developmental Challenges	2022	Production	NA	The essay provides a review of the most critical food security challenges in the context of global development-induced changes and the resulting consequences.	Agriculture and food production are already impacted by climate change. Climate change reduces the availability of water, which causes land drought and the desertification of huge portions of land. Desertification and drought cause the loss of 12 million hectares of land, equivalent to 20 million tons of grain loss.	(Daszkiewicz, 2022)
54	What do changing weather and climate shocks and stresses mean for the UK food system?	2022	Whole food chain	NA	To assess how weather and climate extremes affect the UK food system	Future shocks and pressures brought on by extreme weather events and climatic changes will have a profound influence on the food chain in the UK. There are still significant knowledge gaps regarding their effects on the production of non-cereal crops, livestock, and fisheries, and on food supply chain elements beyond the scope of primary production.	(Falloon et al., 2022)
55	Uncovering the Research Gaps to Alleviate the Negative Impacts of Climate Change on Food Security: A Review	2022	Whole food chain	NA	This paper explored the ways in which climate change affects our food systems as well as the social and economic elements that play a role in achieving fair food distribution.	The potential consequences of climate change are not clear, particularly at the regional levels. Food insecurity problems are predicted to get worse in locations already susceptible to climate change. Human-induced climate change is likely to have an influence on food availability, quality, and quantity, as well as on our capacity to distribute food equitably.	(Farooq et al., 2022)
56	Large variation in availability of Maya food plant sources during ancient droughts	2022	Production	NA	To evaluate the changes in the availability of edible plants during drought periods in the Maya Lowlands	445 plant species have a total of 577 edible parts available during a normal year with no drought. During a short drought, 413 edible plant species will be available for consumption. During moderate drought, 108 food-producing plant species were available. In extreme drought, only 56 edible plant species will be available for consumption.	(Fedick and Santiago, 2022)
57	Pest Management in the Postharvest Agricultural Supply Chain Under Climate Change	2022	Production	Grains, cereals, nuts, and seeds	The review discussed how climate change affects product quality after harvest and how adaptation strategies in food facilities reduce the impact of climate change	Climate change has an influence on insect and pest populations. It is generally recognized that pest/ insects can swiftly adapt to a variety of biotic and abiotic alterations (e.g. pesticide resistance, temperature stress, and disturbance levels). The resilience and adaptive capacity of	(Gerken and Morrison, 2022)

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#	Title	Year	Supply Chain Stage	Food Category	Study objective	Relevant/key findings	Reference
						food facilities to climate change may be boosted by a number of integrated pest management (IPM) techniques.	
58	Climate-related hazards and Indian food supply: Assessing the risk using recent historical data	2022	Distribution	NA	This study quantifies the risks associated with climatic hazards in order to evaluate the probability of detrimental effects on the food supply in Indian States	The results suggest that local production and state-to-state trade might be negatively impacted by climate-related events in India, which could have a negative influence on the nation's food supply.	(Harris et al., 2022)
59	Research priorities for global food security under extreme events	2022	Whole food chain	NA	The goal of this work is to pinpoint food system risks and research opportunities	Multiple food system risks fell into the climate category. This includes combined events such as droughts and heat waves in Sub-Saharan Africa and monsoon and melt water in Asia. The potential of key infrastructure, transportation, and public utility failure that might affect several actors and activities sequentially or simultaneously was one growing issue regarding the food system's sensitivity to cascading hazards.	
60	Sub-Saharan Africa Freshwater Fisheries under Climate Change: A Review of Impacts, Adaptation, and Mitigation Measures	2022	Production	Fish & seafood	This article offers a thorough review of the literature on the impact of climate change on freshwater fisheries, the adaptation strategies employed by fishery-dependent individuals, as well as the management and mitigation measures undertaken to address the problems posed by climate change.	Climate change has various impacts on freshwater environments, such as elevated water temperatures, altered hydrological processes, increased stratification, and heightened pollution. To mitigate the effects of climate-induced fluctuating fishery resources, fishery-dependent communities have implemented diverse adaptation strategies, including fishing gear modification, intensified fishing, species diversification and diversification of their income sources.	(Muringai et al., 2022)
61	Multi-level impacts of climate change and supply disruption events on a potato supply chain: An agent-based modelling approach	2022	Production	Roots & tubers	The objective is to measure the diverse economic consequences of various severe weather occurrences on distinct phases of a food supply network, using the potato supply chain as an example.	The effects of disruptive events vary among agents in the supply chain and product types. During, fresh potato prices increase more than processed potatoes, causing consumers to switch to the latter. This, in turn, aggravates the price increase as processed potatoes require more fresh potatoes as raw material. However, once processed potatoes prices increase due to higher input costs, their demand decreases.	(Rahman et al., 2022)
62	Climate-induced increases in micronutrient availability for coral reef fisheries	2022	Production	Fish and seafood	Determine reef fisheries' nutritional value and climate impacts on availability of micronutrients.	Significant enhancements in the nutrient supply to reef fisheries were observed over a period of twenty years subsequent to coral bleaching, with a notable emphasis on iron and zinc following macroalgal regime alterations. This shows increase in nutritional value of coral reef fish despite climate.	(Robinson et al., 2022)
63	Social-ecological interactions in a disaster context: Puerto Rican farmer households' food security after Hurricane Maria	2022	Production	NA	This paper analyses the food security status of Puerto Rican farmers' households after Hurricane Maria in 2017, using a social-ecological perspective.	In the aftermath of Hurricane Maria, a total of 69 % of farmers suffered from food insecurity for a minimum of one month, while 38 % reported persistent food insecurity lasting for three months or more.	(Rodríguez-Cruz et al., 2022)
64	A district-level analysis for measuring the effects of climate change on production of rice: evidence from Southern India	2022	Production	Grains, cereals, nuts, and seeds	This study examines the impact of alterations in the average values and fluctuation of meteorological variable on rice production by modelling data from 1971 to 2018 in Tamil Nadu State in India.	Rainfall and temperature affect rice yield significantly, according to the results. Also, weather variability, measured by temperature and rainfall standard deviations, has an adverse impact on rice yields.	(Saravanakumar et al., 2022)

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#	Title	Year	Supply Chain Stage	Food Category	Study objective	Relevant/key findings	Reference
65	The Impacts of Climate Change, Carbon Dioxide Emissions (CO2) and Renewable Energy Consumption on Agricultural Economic Growth in South Africa: ARDL Approach	2022	Production	NA	The objective of this investigation was to assess the association between agricultural expansion, climate change, carbon dioxide emissions, and the utilization of renewable energy sources.	In the short term, more carbon emissions are linked to higher productivity and agricultural growth. But over time, this relationship is less significant. When there is less rain and higher temperatures, the farming economy went down in the short term. This means that when climatic variables change, the growth of the farming industry decreases. But in the long term, climate change benefits the agricultural economy.	(Tagwi, 2022)
66	Foresighting future climate change impacts on fisheries and aquaculture in vietnam	2022	Production	Fish and seafood	This evaluates how climate change could affect Vietnam's fishing industry. It focuses on four important types of fish: tuna, pangasius catfish, tilapia, and shrimp.	It is highly probable that climate change will result in significant hydrological changes caused by storm surges, coastal aquifer salinization, saline water intrusion, and coastal erosion. These changes are expected to have a profound impact on aquaculture production systems that are susceptible to water quality, pH, and salinity levels changes, and may lead to the complete fish if inundation occurs. The effects of climate change on Tilapia, Pangasius, Tuna, and prawns in Vietnam will vary depending on their respective habitats, but climate change poses a danger to the sustainable production of each species.	(Tran et al., 2022)
67	Mapping Firms' adaptive profiles: The role of experiences and risk perception in the aquaculture industry	2022	Production	Fish and seafood	The objective of this research is to better understand the adaptive behaviour in the mussel industry in response to climate change in the Los Lagos Region (Chile).	The Chilean mussel production industry is marked by notable heterogeneity, with a coexistence of entrepreneurs, small-scale producers, and large corporations. A significant distinction is evident between the large producers and small to medium-sized enterprises. For instance, more than 50 % of large firms are willing to invest in early warning systems while the majority of smaller firms with lower production capacities are either reluctant to pay or willing to pay values below the average	(Fernández et al., 2023)

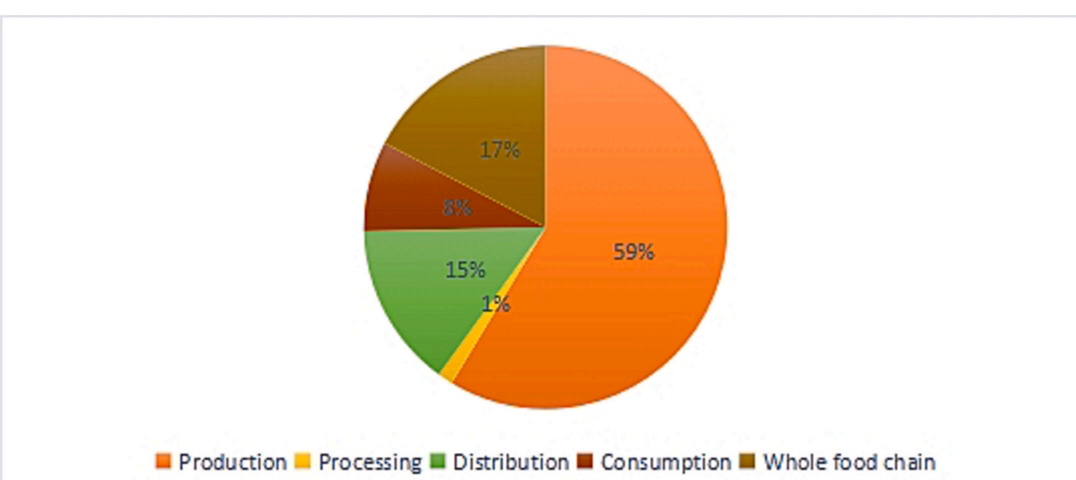

Fig. 4. Distribution of studies according to the supply chain component.

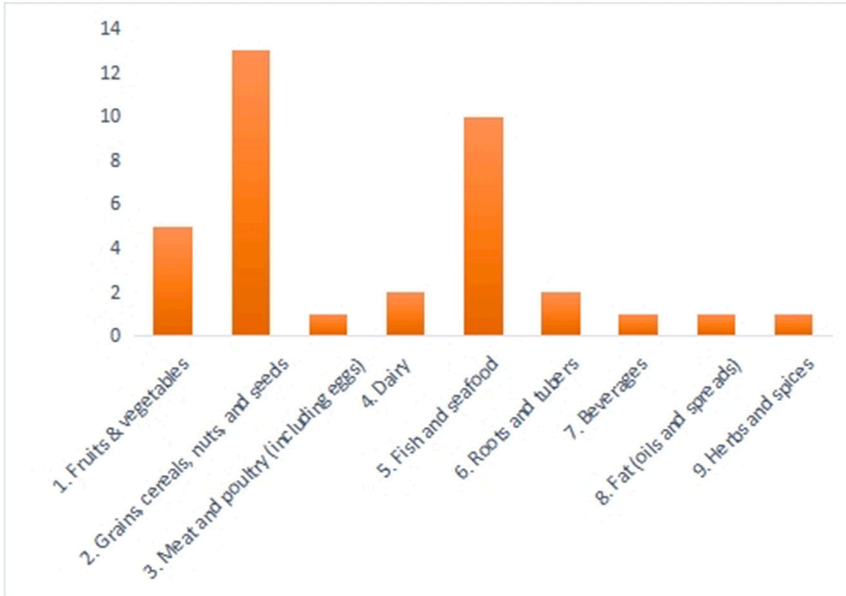

Fig. 5. Number of studies per food category.

accounts for low productivity of oilseed crops in Pakistan, which subsequently affects the local edible oil market (Burhan et al., 2017). Also, plant growth can significantly reduce as a result of flooding that, causes drastic changes in the beneficial soil bacterial population (Francioli et al., 2021).

Food processing operations could be halted in case of damage to food

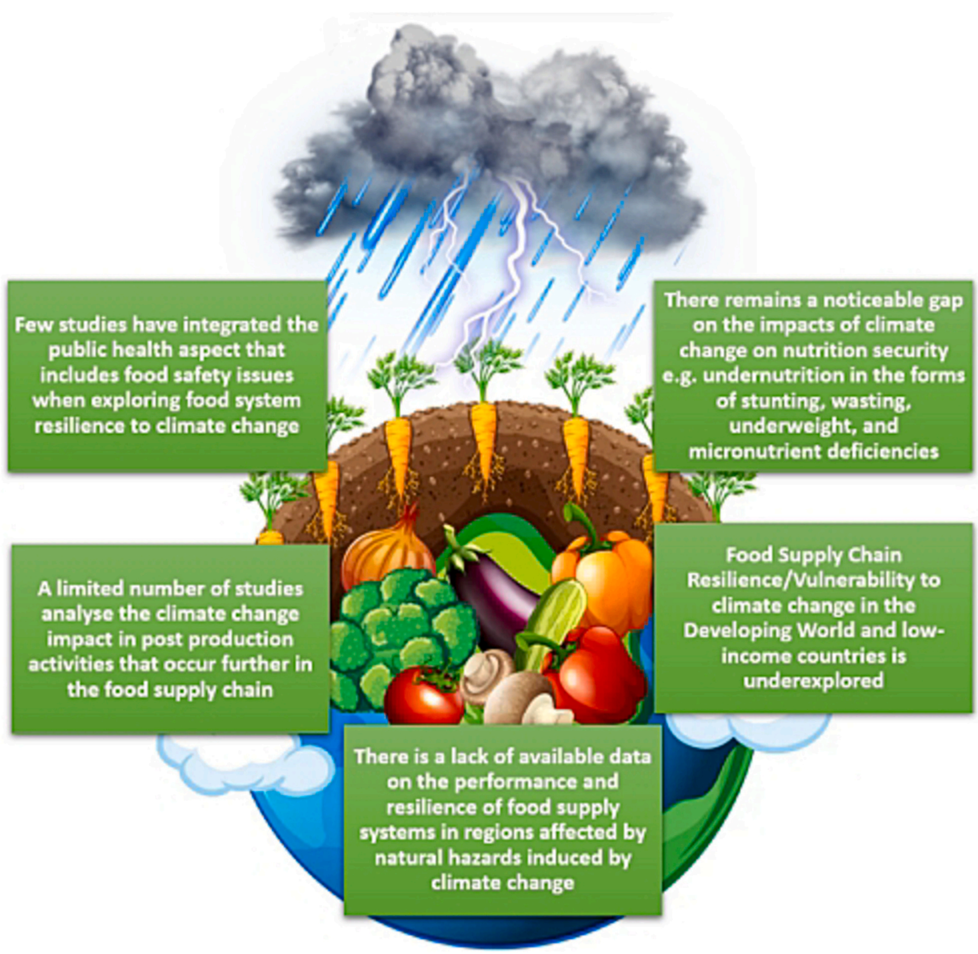

Fig. 6. Identified gaps in literature following database search on climate-induced food supply chain vulnerability.

processing facilities following hazardous events and disturbed food sourcing mechanisms due to lower availability of agricultural raw materials. This leads to higher prices, contributing to the economic inaccessibility of food and beverages. According to Xie et al. (2018), extreme climatic events can potentially reduce barley yields by 3 % to 17 % globally, causing a decreases in global barley supply and shortage of barley grains available to make beer, resulting in dramatic decreases in beer availability and final beer price increases (Xie et al., 2018). Food supply chain failures may hinder access to nutritious foods, leading to malnutrition. Stunting was identified as the most prevalent type of undernutrition among children under 5 in flood-affected regions in low- and middle-income nations (Agabiirwe et al., 2022). It is estimated that the effects of climate change on food security will result in 529,000 additional deaths globally in 2050 (Fan et al., 2021a). Although there is growing evidence on food supply chain vulnerability to climate change, some knowledge gaps that reduce our understanding of the topic were identified (Fig. 6).

(ii) Factors that contribute to the vulnerability of food supply chains

3.4. Smallholders, rural and remotely located communities

Smallholder farmers and rural communities are more susceptible to harm from the effects of climate change because they heavily depend on natural resources for their daily activities and are, in fact, more inclined to conduct farming operations in vulnerable landscapes, including hillsides, deserts, and floodplains (Lennox, 2015). Food producers and consumers in remote areas (e.g. villages and islands), roadless localities, and areas only accessible through waterways (i.e. by boat or ship) are particularly vulnerable to climate change disruptions to local food production and supply because alternative foods from supermarkets, imports and terrestrial sources may be costly, limited, or unavailable (Berger et al., 2020). Due to their geographic isolation, heavy reliance on imported food and beverages, and weak economies, small island nations are particularly susceptible to the effects of climatic and environmental changes. Sea level rise, high tides, cyclones, floodings, and landslides pose a growing threat to coastal and island territories (Lebot, 2013; Orengo Serra and Sanchez-Jauregui, 2021).

3.5. Economic growth and income level of countries

Climate-related disasters impact every territory in both developing and developed nations. Nevertheless, low-income/developing nations, particularly in the Global south, are more vulnerable to climatic anomalies and environmental hazards (Chari and Ngcamu, 2017; Fan et al., 2021a). This is because they tend to lack dedicated, evidence-informed, affordable, and targeted policies to address the potential impacts of climate change on food productivity. In Sub-Saharan Africa for instance, investments are still made based on the supposition that precipitation rates will follow past trends in most cases (Godber and Wall, 2014). However, though they might not be particularly focused on the impacts on food productivity, some low-income nations have implemented policies and measures to address climate change, such as reducing greenhouses gases (GHG) emissions (Assess Vulnerability and Risk, 2023). Regions in the developing world, like Africa, are vulnerable to extreme weather events for the production and processing of food due to significant deficits in key infrastructures and a lack of technology-driven processes (Govindan and Al-Ansari, 2019). The most significant climatic factor found to affect GDP per capita growth in Africa is persistent (prolonged) drought events. Drought has reduced agricultural yields over the past few decades in several African nations (Vicente-Serrano et al., 2012). Over the past 50 years, droughts, floods, cyclones, and earthquakes had detrimental impacts on the agribusiness value chain of Mozambique, causing an estimated 5000 metric tons of cereal deficit annually. The overall milk production from various farming areas was reduced due to animal diseases associated with extreme temperatures in Peru as well as droughts, veld fires, and extreme weather events in Southern African countries like Zimbabwe (Lennox, 2015; Chari and Ngcamu, 2017).

3.6. Food type and region of origin

The vulnerability varies greatly for each food product and production/exporting region. For example, climate vulnerability analyses of key agricultural products imported by the European Union (EU) revealed that the susceptibility to drought for sunflower seeds and maize is low. In contrast, the vulnerability to drought for coffee, cocoa, and palm oil is very high. Moreover, coffee from Indonesia, Brazil, and Vietnam is more vulnerable to drought than Colombia, Uganda, Peru, Ethiopia, and Kenya (Ercin et al., 2021). In the Indian state of Punjab, the wheat yield was estimated to be negatively impacted by a 5 % rainfall coefficient, and a 1 °C rise in maximum temperature reduces wheat harvest by 2.012 %. A 10 % rise in rainfall negatively affects rice productivity, and a 1 °C rise in the maximum temperature resulted in a 2.606 % reduction in rice yield (Saravanakumar et al., 2022). In the Mediterranean region, it is anticipated that wheat and legume crops, which have an essential part to play in feeding people and livestock, will be among the crops most negatively impacted by the anticipated more regular and intense drought events (Tramblay et al., 2020). A climate catastrophe in one region may affect the national or wider food supply, especially if that area is a food production hub. Therefore, knowledge of where food is sourced is crucial for characterizing climate risks to food security and guiding adaptation strategies (Harris et al., 2022).

3.7. Reliance on the ocean economy

Greater frequency or degree of coral bleaching, sea level rise, rising water temperatures, and altered currents, have been identified as risk factors in the seafood industry, leading to modifications in catch potential, changes in species distribution, loss of productivity, and changes in the food supply of seafood (Fleming et al., 2014; Robinson et al., 2022). Floods and droughts are widely acknowledged as potentially posing a serious threat to the fisheries industry now and in the future (Tran et al., 2022). Declines in wild fish populations (stocks), fish diversity and aquaculture output, along with changes in species distribution, are exacerbated by changes in climatic conditions. For over fifty years, fishermen in southern Chile have been concerned about HABs, which prevent the consumption of aquatic products such as fish and molluscs (Berger et al., 2020). As a result of habitat degradation driven by a warming planet, models projected that cold water fish species would disappear from their current range in Canada while warm water species may augment their habitat range (Brain and Prosser, 2022). Growing food safety concerns about the rising incidence of infectious diseases among aquatic organisms exist. Additionally, the increased regularity of extreme weather events associated with climate change could have detrimental effects on the channels used for processing, packaging, and distribution, which would further reduce the availability of seafood (Cooney et al., 2023).

3.8. Infrastructural facilities

Pre-hazard conditions equally influence vulnerability to disruptions. The inexistence of adequate infrastructure before climatic hazards can lead to an increase in the duration of the disruptions and a decrease in disaster readiness, hence raising vulnerability (Dargin et al., 2020). Consequently, the food supply chain is subject to operational risks due to the deterioration of infrastructure and associated services (Govindan and Al-Ansari, 2019). Absence of safe water and sanitation systems facilitates access to pathogenic bacteria, parasites, mycotoxins, and a variety of viruses when precipitation extremes (both higher rainfall and persistent drought conditions) occur (Myers et al., 2017). The transportation networks are highly vulnerable to climate change-induced natural hazards (e.g. floods). The constant provision of food along wider food supply change is at risk because agro-industrial products now traverse greater distances from the supplier to the final consumer due to globalization (Parker et al., 2019).

(iii) Approaches to assessing the vulnerability of the food supply chain to climate change?

The vulnerability approach is used to evaluate how resilient the food supply chain is to climate change-derived trends and hazards. The capacity of a defined entity (in this case the food supply chain) to withstand perturbations or shocks while retaining crucial structures and functions is known as resilience. It refers to the ability to successfully recover from disturbances without a loss in primary purpose. On the other hand, vulnerability is defined as being susceptible to stress derived from environmental and societal changes and lacking adaptability (Proag, 2014; Nelson et al., 2016). For example, crop vulnerability measures how at risk a crop is to climate change-derived drought and water scarcity and how well it can withstand those hazards. Therefore, as the supply chain's vulnerability decreases, its resilience increases (Yue et al., 2018).

Evaluating the impact of climate change on different food supply chains is a difficult task because a given climatic event of equal severity can have different effects in different regions and systems due to underlying vulnerabilities and adaptive capacity (Chari and Ngcamu, 2017; Fan et al., 2021a). High-quality data is required to evaluate the effects of and vulnerability to climate change to design adaptation strategies. This data includes measurement and monitoring of climatic variables, such as temperature, snow and ice cover, rainfall, sea level rise, wind speed, and the magnitude and frequency of extreme events, as well as non-climate-related information on water resources, agriculture, food security, public health, terrestrial ecosystems, biodiversity, and coastal zones (UNFCCC, 2007). For instance, to determine the vulnerability of coastal agricultural systems to the intensification of tropical cyclones and storm surges, it is necessary to monitor sea surface temperature and sea level rise. It is worth mentioning that the nature, intensity, and frequency of climate variability influences vulnerability. Furthermore, the climate vulnerability of the food supply chain varies from one country, region or community to another and within specific sectors (Climate Adapt Impacts, Risks and Vulnerabilities — English, 2023).

Therefore, a vulnerability assessment is a procedure which involves the identification, quantification, and prioritization of a system's (i.e. food supply chain) vulnerabilities to a disturbance or hazard (i.e. climate change) (Altaf et al., 2015). This is necessary to determine whether the food supply chain is susceptible to climate change and to what extent (Feindouno, 2018). Also, it enables the description of risk profiles. In other words, determining which element is more likely or less likely to experience damage across the food supply chain. Evaluating climate vulnerability is more cost-effective than not being prepared for a future catastrophe (Climate Change Quantitative Vulnerability Assessments, 2023).

3.9. The three component-approach of vulnerability

According to the theory framework of the IPCC, there are three components for assessing vulnerability and obtaining a vulnerability rating: exposure, sensitivity, and adaptive capacity. The combination of these three elements is used to analyse the likelihood that climate change would have a negative impact on a system. The term "exposure" refers to the type, degree, and aggregation of climatic variations that a location experiences as a result of factors like temperature, precipitation, and severe weather (Baca et al., 2014; Parker et al., 2019). Exposure is the only factor directly related to climate parameters, including the nature, severity, and rate of the variation in climate (Fritzsche et al., 2014). Sensitivity measures the likelihood of being impacted or the nature and potential degree of the impact of climate change on various processes (e.g. the extent to which crop yields or human nutrition might be affected). Some indicators of sensitivity include prevalence of food insecurity and self-sufficiency (Godber and Wall, 2014). To determine whether a system or entity is vulnerable, the system's sensitivity to the hazardous event it is exposed to should be considered. Is the food supply chain or elements of the food supply chain susceptible to damage from the hazard? (Assess Vulnerability and Risk, 2023). Adaptive capacity is the capability of a system to adapt to climate change, to lower or mitigate potential damage or to take advantage of opportunities derived from the changing climatic variables (Baca et al., 2014; Fritzsche et al., 2014). Indicators of adaptive capacity include the population's health and the performance of the economy (Godber and Wall, 2014). Understanding the adaptation potential of the food supply chain is crucial because although an element of the food supply chain is sensitive to a climatic hazard, it is not inherently vulnerable if it possesses the ability to cope with or adapt to climate-related risk or consequences. An effective way to deal with climatic hazards and unpredictability is to improve adaptive capacity. Nevertheless, adaptive capacity is significantly influenced by access to resources and the cost of using those resources (Saeed et al., 2023).

Li et al. (Li et al., 2015) analysed the vulnerability of China's agricultural sector to climate change as a function of the three components: exposure, sensitivity, and adaptive capacity. The study highlighted the effectiveness of using multiple indicators to assess climate vulnerability and showed that agricultural vulnerability is already important in Guizhou, Guangxi, and Yunnan provinces, with a high probability of worsening in the 2040s. The three components of vulnerability have been used previously to assess the vulnerability of fisheries (Allison et al., 2009; Gómez Murciano et al., 2021) and livestock (Godber and Wall, 2014). All these studies reported that most of the world's underdeveloped nations are most at risk from climate change's effects because poorer regions lack adequate adaptive capacity.

3.10. Vulnerability index

A vulnerability index has been created to measure the susceptibility of different areas or entities to climate-related events. To determine the areas or entities with the highest vulnerability, data analysis methods such as cluster analysis, gray system theory, and principal component analysis were used. This was done by assigning weights to environmental, sensitivity, and adaptability indicators (Feng and Chao, 2020). For example, Yeni and Alpas (Yeni and Alpas, 2017) used the three-component approach (exposure, sensitivity and adaptability) as a tool to identify the extreme weather patterns that threaten food safety by comparing the performances of 118 countries to maintain the safety of food production in the face of climatic hazards based on a ranking of the countries' vulnerability index scores. Similarly, selected indicators were assigned a score to create a vulnerability index for dynamic floods in mountainous regions (Papathoma-Köhle et al., 2019). The indicators are elements linked to the climatic hazards which can reveal details about the features of the event (Bottero, 2011). Nevertheless, Guo et al. 2021 stated that establishing quantitative relationships between the magnitude of the environmental phenomenon and vulnerability indices is challenging when utilizing a variety of indicators that are difficult to compare in indicator-based vulnerability assessments. Therefore, quantifying the potential loss or damage from climate change is limited (Guo et al., 2021).

3.11. Vulnerability curves

Several researchers generated physical vulnerability curves (Fig. 7) as a means to quantify the vulnerability of crop value chains such as wheat (Wang et al., 2013), rice (Guo et al., 2021), and maize (Wang et al., 2016) to climate change-related events and natural disasters. Vulnerability curves demonstrate how vulnerable a physical system is

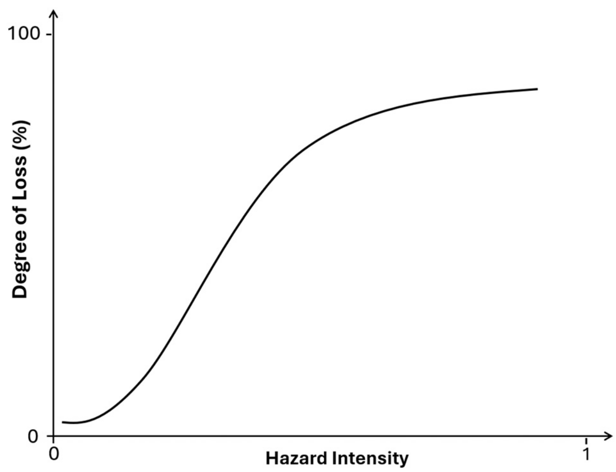

Fig. 7. Illustration of a vulnerability curve to climate change and natural hazards.

based on two factors: the severity of the hazardous event and the magnitude of the potential loss (Papathoma-Köhle, 2016). In the agricultural industry, crop yield represents hazard exposure, while the drop in crop productivity relative to the yield expected under normal climatic conditions defines the vulnerability, hence reflecting the harm caused by the hazard to an asset (like arable land, for example). In numerous studies, the scale used to describe the damage caused to the asset ranges from 0 (no loss) to 1 (complete loss) (Monteleone et al., 2022). The development of physical vulnerability curves comprises using models (e.g. EPIC, ORYZA and WOFOST) to simulate the growth of plants under different environmental conditions to determine the impact of climatic variability on crop growth (Guo et al., 2021; Antle and Capalbo, 2010; McMaster et al., 2014).

3.12. Censuses and surveys

Censuses and surveys are for providing most of the data used to measure indicators of adaptive capacity (and, to a lesser degree, sensitivity), thus assessing vulnerability in the food supply chain (Fritzsche et al., 2014). Harvey et al. conducted surveys consisting of 197 questions in 10 villages in Madagascar to assess the vulnerability of smallholder farmers to climate change. This research highlighted the vulnerable state of Madagascar's smallholder farmers, their high risk exposure, and the pressing need to lessen their present and future vulnerability to these risks (Harvey et al., 2014). Other vulnerability assessment methods include vulnerability simulation based on the process-based physical model simulation (Feng and Chao, 2020), and top-down & bottom-down vulnerability analysis (Nelitz et al., 2013; Kao et al., 2016).

(iv) Effectiveness of different strategies for enhancing the resilience of food supply chains to climate change-induced disruptions?

A wide range of resilience measures have been employed and suggested to alleviate climate change consequences in the food supply chain. Climate-resilience strategies incorporate both mitigation and adaptation (Mbow et al., 2014). Mitigation aims to reduce the escalating industrial causes of climate change and its negative consequences. In contrast to mitigation, adaptation refers to adjusting (coping) to current or projected environmental conditions, particularly their associated impacts, to prevent damage. Strategies should assist in reducing impacts to the point where the function of the system is guaranteed or can be restored to its normal state in the shortest amount of time (Pyykkö et al., 2021; Reddy, 2014). Resilience in supply chain management refers to "the ability to respond to a sudden disruption (or shock) and resume normal supply network processes and operations" (Rice and Caniato, 2003).

Each country's circumstances, ability, and resources should be considered when developing climate change resilience strategies. Solutions can be expensive, particularly when there is little financial room available. Using initiatives from the private sector, such as startup innovations, is one of the options that national governments should closely consider. Enhancing water management, modifying sowing and harvest times, disseminating knowledge, and adopting new crop varieties and livestock breeds that exhibit tolerance or resistance to unfavourable conditions are examples of high-impact adaptation strategies (Rother et al., 2022).

Improving access to information (e.g. through early warning systems, disseminating weather and price information), encouraging research and development initiatives, and implementing risk management, and training programs for agricultural producers are the most effective ways of reducing vulnerability to crop and livestock yield reductions due to climate variability (Sofi et al., 2019; Raza et al., 2019). Implementing efficient integrated monitoring systems is an important adaptation strategy. This entails using surveillance systems to provide sufficient details on the physical and chemical changes in environmental conditions, the existence of pests, including harmful algal blooms, and the early discovery of diseases (Perez et al., n.d.). Mitigating strategies usually target carbon sequestration by increasing carbon capture in the agricultural and agroforestry systems, as well as reduction of GHG emissions/preventing future emissions, via improved productivity, enhanced input efficiency, reduced food loss or waste, adoption of diets based on foods with lower carbon footprints, and conservation of forests (Campbell et al., 2016).

Furthermore, governmental programs that implement insurance schemes to compensate farmers for damage caused by environmental shocks both in the short and long term are necessary. These compensation plans could incentivise farmers to use more modernized agricultural techniques, reducing countries' dependence on food imports and raising food self-sufficiency and security (Saravanakumar et al., 2022). Switching to cooperative agricultural production could, however, effectively lessen or disperse crop failure risk due to hailstorms, which are hazards that are usually very isolated geographically (Lennox, 2015).

Food banks and disaster response organizations could set up buffer stocks or backup distribution points in areas that are likely to experience significant disruptions or isolation (Casellas Connors et al., 2022). Infrastructures should be built to continue operating during and after climatic hazards and offer similar services as expected under normal climatic conditions (Dargin et al., 2020). Capacity building is frequently, if not always, a necessary component of climate change adaptation efforts to improve the management of climatic hazards. This includes programs that contribute to augmenting skills in drought management & planning, particularly in the use of geospatial drought information products to assess the risk and vulnerability to drought, as well as to develop surveillance and early-warning mechanisms that use live data to aid decision-making (Vicente-Serrano et al., 2012). Adaptive governance, which involves leveraging past experiences to plan for future uncertainties, can enhance food supply stability under changing climatic conditions (Mason et al., 2022). Table 3 summarizes the climate change adaptation and mitigation strategies that are discussed in the present study.

a) Reduction of greenhouse gas (GHG) emissions

GHG emissions are used to estimate the carbon footprint of each food system activity. Nowadays, the term "carbon footprint" refers to all GHGs that contribute to climate change, not just CO_2 or other carbon-derived GHG (Filho et al., 2022). The agricultural and food supply chain GHG emissions increased by 17 % from 1990 to 2019. The overall global emissions from agri-food system activities in 2019 were 16.5 billion metric tonnes (Gt CO2 eq. yr^{-1}), equivalent to 31 % of all

Table 3
Summary of effective climate change adaptation and mitigation strategies.

Type	Description
Reduction of GHG emissions	Reducing the emission of GHGs from food production activities and post-production operations through waste management and valorisation approaches such as recycling, composting, preventing the disposal and wastage of food
Agricultural systems resilience strategies	This involves enhancing soil quality (e.g. by improving the efficiency of fertilizers, employing reduced tillage, reducing salt levels), using of climate resilience crops, improving water usage efficiency (e.g. rainwater collection, water reuse, water-saving irrigation techniques), using weather forecasting and early warning systems, and adopting adapted culture techniques such as agroforestry, intercropping and mixed-crop livestock system.
Animal husbandry resilience strategies	This includes approaches such as improving breeding strategies and using genetic improvement to enhance animal resilience, adjusting feeding regimes to optimize feed efficiency and nutritional value, combating thermal stress, and improving pasture management to reduce damage to pasture and forage crops.
Aquaculture and fisheries resilience strategies	Recommended techniques include adopting integrated systems (e.g. integrated aquaculture-agriculture), diversifying production (for example by farming multiple fish species), breeding farmed species for tolerance, resilience traits, or improved growth rates, using water-efficient systems such as recirculating aquaculture systems, and implementing monitoring systems of climatic variables and early notification systems.
Post-production activities resilience strategies	This includes using green and energy-efficient technologies such as non-thermal processing, reducing water consumption, shifting to biodegradable/sustainable packaging, reducing food waste from processing, distribution, and consumption, building cold storage facilities and use of refrigerated transportation.

emissions produced by anthropogenic activities. Global emissions from crop and livestock production processes accounted for 7.2 metric tonnes, and pre-and post-farming operations (such as the production of fertilizers, food processing, packaging, transportation, retail, final consumption, and disposal of agrifood waste) accounted for 5.8 metric tonnes (Tubiello et al., 2022). GHG emissions and, consequently, climate change, are significantly exacerbated by food waste. There are significant opportunities for reduced GHG emissions from food chain activities by improved waste management and optimizing processes and resource utilization (Filho et al., 2022).

Several countries worldwide have integrated the recycling of biodegradable food waste (including kitchen waste and waste from food processing factories) into their waste management policies to reduce GHG emissions. Preventing the disposal and wastage of edible foodstuffs, also known as food loss, is essential to reduce GHG emissions (Matsuda et al., 2012). By changing the "use by" and "best by" date labelling and educating consumers about the meaning of these labels, a shift in consumer food disposal behaviour could be initiated to prevent food products that can still be eaten from being discarded earlier (Gustafson et al., 2021).

Anaerobic digestion (AD) and composting are viable means for the sustainable treatment of food waste that lowers GHG emissions without compromising the nutritional content of the waste substrate (Filho et al., 2022; Xu et al., 2018; Moraes et al., 2017; Grigatti et al., 2020). AD is a controlled process during which a mixed culture of symbiotic microorganisms degrades organic waste without air, producing digestate (fertilizer) and biogas (methane). Biogas can then be used as a renewable energy source to generate heat or electricity (Gautam et al., 2019). Composting is the decomposition of organic waste in aerobic conditions by microorganisms, converting the waste substrate into a more stable form of organic matter. Heat and CO_2 are released in the process. (Kumar, 2011).

AD is usually preferred for the treatment of food waste, in comparison to composting, due to improved sustainability related to lower GHG emissions (Moult et al., 2018). AD may be more profitable for large-scale or centralized biowaste processing, such as food waste or sewage; whereas, composting may be preferable for smaller-scale and decentralized waste processing directed to waste feedstocks such as on-farm livestock manure (Lin et al., 2018). Furthermore, producing biogas and nutrient-rich digestate during AD improves energy, food, and water security. This is because the digestate can be used as soil fertilizer, and the production of methane-containing biogas decreases the water consumption associated with the production of energy from fossil fuels (Lin et al., 2018; Yang et al., 2014). Further mitigation of GHG emissions can be achieved through producing bioethanol from food waste by employing fermentation. It is an eco-friendly fuel that improves air quality, boosts rural household economies, and reduces GHG emissions by 70–90 % (Roukas and Kotzekidou, 2022). However, additional research is necessary to render the food-waste-derived biofuel synthesis more feasible by overcoming a few technical challenges associated with pre-treatment and conversion of food waste into bioethanol (Kazemi Shariat Panahi et al., 2022).

b) Agricultural systems resilience strategies

Climate change significantly affects the agriculture of a given region (Raza et al., 2019). Consequently, governments should invest in tillage techniques, genetic improvement, and modern planting technologies that allow grain and crop output to adjust to shifting climatic conditions. Secondly, the employment of sophisticated climate-smart farming practices, such as permanent irrigation and new crop varieties that demand less water and are highly productive under high temperatures, will help in preventing reduced yields of significant crops like wheat and rice (Ragagnin et al., 2018). Actions to be taken to protect the vital pollination process required for crop production include measures that involve the management of cultivation sites by putting forage plants close to crops, providing bee nesting areas, and preserving native grassland since fragmentation and loss of habitat are a serious danger to pollinators (Bekchanov and Lamers, 2016).

3.13. Soil management

Enhancing resilience of agricultural soils can be achieved through improved tillage management (e.g. zero tillage) to reduce GHG emissions, performing soil analysis for efficient application of fertilizers based on results, application of manure on agricultural fields, avoidance of bare cropping land, using appropriate plant varieties like legumes as green manure (cover crops) (Bakala et al., 2020; Gross and Glaser, 2021; James and Merfield, 2021), and decontamination of soils using phytoremediation, a "green-clean" and low-cost technology that degrades or removes toxic contaminants, to increase agricultural output on polluted lands (Dhankher and Foyer, 2018).

The absorption of atmospheric CO_2 by soils (known as soil organic carbon(SOC) sequestration) enhances fertility, ensures long-term productivity of plots, and combats climate change through the reduction in atmospheric CO_2 (Tessema et al., 2020). Mitigation measures for SOC sequestration may assist cropping systems in coping with floods and droughts (Rosenzweig and Tubiello, 2007). Conservation ploughing, crop rotation with legumes, application of cover crops or manure, integrated nutrient management, irrigation management, agroforestry (tree-planting), and grassland/pasture management are among soil management practices for the restoration of SOC (Elbasiouny et al., 2022).

Legume cover crops can reduce nitrous oxide gas emissions, which are highly associated with applying nitrogen (N) fertilizer and soil nitrate (NO_3^-) in agricultural soils. According to research by Mahama et al. (2020), cumulative nitrous oxide (N_2O) emissions were higher in crop production systems in which nitrogen fertilizer (180 kg/ha and 90 kg/ha) was used than in nitrogen-free systems that used cover crops (Mahama et al., 2020). In cereal cultivation, enhanced efficiency fertilizers (EEFs) have been suggested as a possible approach to reduce N_2O emissions. Scheer and co-workers observed that two EEFs (urea with the nitrification inhibitor 3,4-dimethylpyrazole phosphate and polymer-coated urea) decreased yearly N_2O emissions from soils by 83 % and 70 %, respectively (Scheer et al., 2016).

3.14. Salt levels management

Reclamation of saline lands and reduction of salt salinity levels via techniques such as flushing of surface salts with water, scraping (mechanical removal of salt), leaching (removal of excess salts from soils with irrigation, rain or extra water), surface & subsurface drainage to prevent accumulation of salts, and addition of organic and mineral amendments (e.g. compost, gypsum, molasses, leonardite, zeolites, etc.) to regulate pH and improve the physicochemical composition of the soil (Medina Litardo et al., 2022; Mary et al., 2020). Sustainable irrigation methods can be employed for soils with higher-than-normal salt content. For example, alternate application of good quality and saline water separately using spray or drip irrigation techniques to leach salts from the plant's rhizosphere, such irrigation technique equally improves water use efficiency (Hanson and May, 2010).

3.15. Climate-resilient crops

Adopting improved plant cultivars with tolerance/resistance to stresses such as low-water availability, drought, heat, high-salt environments, flooding and using other climate-resilient crops such as early maturing crops can prevent declines in yields improve and resilience. Introducing tolerant characteristics is a sustainable way to lower the risk of crop failure because it enhances a crop's ability to survive for extended periods in sub-optimal conditions, reduces crop water demands, and improves water use efficiency (Sofi et al., 2019; Acevedo et al., 2020). For example, using rice varieties that are submergent-tolerant mitigates the risk of a decrease in rice productivity due to rice paddy field flooding since submergence stress causes severe damage and is deadly to rice seedlings (Dhankher and Foyer, 2018). Although relatively few studies exist on the subject, de novo domestication has been proposed as a promising technique to improve crop resilience for food and feed production. This entails selecting wild plant species that exhibit a natural resistance to climatic stresses, improving their productivity through mutations mimicking domestication procedures of major food crops, and performing iterations of conventional plant breeding (Zsögön et al., 2022; Fernie and Yan, 2019).

3.16. Better management of water resources

Improvement of water usage efficiency in agricultural systems through the installation of more efficient irrigation systems like water-saving irrigation technologies, recycling, and reuse of wastewater in farms to adapt to the predicted decrease in rainfall and groundwater, and to alleviate water scarcity and environmental issues, such as excessive groundwater pumping for irrigation in arid areas and/or areas with extreme water shortage (Liu et al., 2020; Niu et al., 2022). A growing number of regions respond to water scarcity by implementing rainwater collection systems such as inter-row harvesting, inter-plot harvesting, and water storage in farm ponds, tanks, and reservoirs (Bakala et al., 2020). For instance, collected rainwater irrigates cultivated fields in Burkina Faso (Rother et al., 2022).

3.17. Weather forecasting and warning strategies

Improvement of weather forecasting can be achieved by installing automatic weather stations on farms and observatories to gather up-to-date information on weather conditions such as rainfall, temperature, and wind velocity. This is useful for disseminating up-to-date climatic data and divulge warnings related to unfavourable weather conditions (e.g. drought) in farming communities (Reddy, 2014; Bakala et al., 2020). This will aid farmers in identifying suitable planting times (Codjoe and Owusu, 2011). In addition, incorporating vulnerability curves in early warning systems is useful in supplying details on the potential effects of upcoming climatic conditions on agricultural productivity and can therefore assist farmers in their selection of cultivars, planting dates, and crop management practices (Guo et al., 2016).

3.18. Adapted cultivation systems

Adapted culture techniques such as diversification of production through the practice of agroforestry (incorporating perennial trees into crop cultivation), mixed crop-livestock farming, crop rotation, and intercropping (e.g. legume-cereal cropping system) have a high potential to improve the performance of cultivated crops despite climate change (Bakala et al., 2020; Teixeira et al., 2018). Crop rotation aids in weed, disease, and bug control. Reduced on-farm GHG emissions were achieved by including grain legumes in crop rotation, improving crop methane uptake. Also, there is a negative association between crop rotation and soil erosions (Barton et al., 2013). Mixed farming strategies consisting of diverse trees, crops, and livestock preserves biodiversity, prevent soil erosion, reduce harm from flooding, and improve water storage, thus increasing productivity and efficiency while using fewer resources and land (Sistla et al., 2016). Livestock provides manure to crops, while crop remains are fed to livestock in mixed farming (Osei-Amponsah et al., 2019).

c) Animal husbandry resilience strategies

Climate change has a negative impact on animal production outputs as well as the quantity and quality of animal feed. Therefore, adaptation and mitigation strategies are crucial to reduce climate change vulnerability in animal husbandry.

3.19. Breeding and genetic improvement

Improving breeding techniques can enable animals to be more resilient to diseases and heat duress while enhancing their growth and reproductive capacity (Rojas-Downing et al., 2017). Genetic improvement is a more profitable adaptive approach that results in a long-lasting change in the animal flocks and herds. This could be achieved by performing genetic selection for stress tolerance to conditions like heat and disease. A path forward could be identifying local breeds adapting to environmental stresses and introducing stress-tolerant genes in these breeds (Osei-Amponsah et al., 2019).

Scientists examined the selection strategies of heat-tolerant animals in farms. The complexity of the thermal adaptation responses and the antagonistic effect between thermal tolerance and productivity make selection a difficult task. The use of inexpensive tools to identify phenotypic heat stress biomarkers is a suggested selection procedure. In addition, omics technologies are required to generate genomic indices to select the best breeding group (Carabaño et al., 2019). A study by Hammami et al. (2015) highlighted that the individual milk fatty acid, oleic acid (C18:1 cis-9) could be an affordable thermal stress biomarker (Hammami et al., 2015). Incorporating genetic improvement for heat tolerance in the selective breeding of animals with good product performance will be more advantageous to animal husbandry systems that possess resources for the mitigation of heat, suitable nutritional supply, and control of pathogens and parasites. Contrastingly, crossbreeding local animal groups with speciality breeds possessing high productive abilities will be more advantageous for farms with limited resources (Bernabucci, 2019). More than 85 % performance improvement in broiler and layer poultry varieties is been attributable to the genetic development of production breeds aimed at optimizing feed conversion efficiency by breeding programs, along with adequate nutrition (Athrey, 2020).

3.20. Changes in animal feeding

To deal with the issue of lower quality animal fodder or to ensure adequate nutrient intake during unfavourable weather conditions such as extreme heat, feeding regimes can be adjusted by adopting various practices such as modifying feed formulation to enhance its nutritional value, changing feeding schedules and frequency to cooler times of the day (e.g. early morning or evening), adding tree crops from agroforestry to the animal's diet, and educating farmers on producing and preserving forage for optimal feedstock management based on different agro-ecological zones (Rojas-Downing et al., 2017). The detrimental effects of heat stress on chickens could be minimized by feeding them more herbal additives (e.g. *Artemisia annua*, moringa, rosemary), fat supplements (e.g. palm oil), and low protein diets (Nawaz et al., 2021). It is well known that changes in feed strategies, such as introducing water to the animal feed, substantially improve farmed animals' well-being. When compared to no-water feed at normal temperatures, wet feeding advantages include increased feed intake, body weight gain, increased growth rate, feed conversion efficiency, and reduced wasting of feed and water (Chae, 2000; Naga Raja Kumari and Narendra Nath, 2018). When corn silage is used in lieu of grass silage in the diet of ruminant animals, methane emissions can be decreased. Due to their reduced fibre content compared to grass silage, using legume silages to feed animals could also reduce methane emissions (Hristov et al., 2018).

3.21. Heat stress alleviation

According to references (Hristov et al., 2018; Sossidou et al., n.d.), mitigating the impact of thermal stress on livestock can be achieved through the implementation of measures such as using natural or artificial shades for sun protection, utilizing evaporative cooling and mechanical ventilation. These practices help to maintain the animals' energy requirements at levels equivalent to those of a normal temperature range since they may require more energy for maintenance and thermoregulation when temperatures are high. Elevated temperatures reduce feed intake. Hence, It's essential to meet energy and nutritional requirements despite a lower feed intake by farmed animals, particularly when combined with increased water consumption to regulate body temperature (Naga Raja Kumari and Narendra Nath, 2018). Anzures-Olvera et al. (2015) found that the milk output of Holstein cows decreased by 50 % in the summer without a cooling system (Anzures-Olvera et al., 2015). Excessive reductions in meat and milk production in high temperature seasons could be avoided by installing water supply systems to ensure that animals have access to sufficient water, housing animals in facilities with high ventilation, modifying feeding schedules, avoiding moving or handling livestock during the hottest times of the day, and using misting fan systems (Theusme et al., 2021). Liang and colleagues indicated that sprinkler technology reduces heat stress in poultry farms and uses 66 % less water compared to evaporative cooling systems (Liang et al., 2020).

3.22. Management of pasture

Reduced carrying capacity of pasture to levels at which animal husbandry production activities become unprofitable is one of the most severe potential climate change impacts on ranching. The confluence of rising summer temperatures and an increase in the frequency of drought causes this decline. Minimizing damage to pasture and forage crops is possible by shifting to rotational grazing (Holechek et al., 2020). A study by Dong et al. (2020) reported that rotational grazing under moderate grazing intensity may preserve or enhance grasslands' height, cover, productivity, and biodiversity. It may also decrease GHG emissions in the ecosystems. (Dong et al., 2020). Rotational grazing improves livestock production because more animals can be nourished on the same land area resulting in more efficient use of the pasture (Rolando et al., 2017).

d) Aquaculture and fisheries resilience strategies

The direct effects of climate change on fisheries and aquaculture include further declines in production due to rising sea levels, ocean acidification, and warming waters (Dey et al., 2016). The implementation of adaptation and mitigation measures to climate change in the seafood industry is presently limited. This is partially due to the absence of political incentives to recognize and develop preparedness for climate change effects (Bryndum-Buchholz et al., 2021). Several approaches have been recommended to overcome present obstacles and support adaptation to climate change in the fishing sector.

3.23. Production diversification and integrated systems

Diversification of production systems in the form of polyculture (i.e. simultaneous production of multiple fish/aquatic species such as IMTA-integrated multi-trophic aquaculture), and integrated aquaculture-agriculture (IAA) systems (e.g. fish-vegetable farming, rice-fish culture, pond-dike cropping, etc.), to optimize resource utilization and to increase climate change resilience of aquaculture (Reid et al., 2019; Limbu et al., 2017).

Polyculture of six to eight carp varieties led to a productivity rise from 12 to 15 tons per hectare per year to 30–40 tons per hectare per year (Miao and Yuan, 2007). Similarly, the production output from an IAA system using fish and vegetables was 3 and 2.5 times greater than fish and vegetables farmed alone, respectively (Limbu et al., 2017). The most frequent beneficial interactions between agriculture and aquaculture in IAA systems involve using livestock manure as nutrient-rich fertilizer for crops, using crop by-products as supplemental fishmeal, using fish pond sediments as inland crop fertilizers, and crop irrigation using aquaculture wastewaters (Zajdband, 2011). For example, rice-fish co-culture is a sustainable farming system that allows simultaneous fish farming and rice cultivation in the same area, thereby minimizing GHG emissions and reducing pressure on water resources and agricultural land (Saiful Islam et al., 2015). Fish inhale dissolved oxygen and release carbon dioxide, which rice plants use for photosynthesis. Fish movement and foraging for food in rice fields excrete phosphorus and nitrogen, which enriches soil fertility by increasing the availability of phosphorus and nitrogen in rice paddies.

Furthermore, fish consumes pests and weeds, creating weed-free rice environments and reducing the use of herbicides and pesticides (Zajdband, 2011; Ahmed and Turchini, 2021a). Dike-pond systems can aid fish in coping with warmer water, hence reducing thermal stress. Growing vegetables and planting fruit trees on fish pond dikes provide shade to the fish (Ahmed and Diana, 2016).

3.24. Selective breeding for quality traits

Employing well-designed breeding strategies to support the sustainable genetic improvement of economically important traits, such as heat or cold tolerance, salinity tolerance and disease resistance, has a great potential to satisfy the growing demand for seafood in the face of climate change (Houston et al., 2020). Farmed oysters selectively bred for rapid growth and disease resistance were more resilient to ocean acidification due to their ability to adjust their shell development mechanism (Abisha et al., 2022). Breeding species for increased growth rate can be used as a strategy to increase feed conversion efficiency because selective breeding for rapid growth improves feed utilization efficiency. This enables higher production with lower feed consumption, thus lowering production cost (Sae-Lim et al., 2017). A frequent cause of farmed fish production loss is the occurrence of disease caused by fungi, virus, bacteria, and parasites. According to Gjedrem et al. (2015), breeding programs to increase disease resistance can raise the percentage of survival by minimum 12.5 % per generation in fish and shellfish (Gjedrem, 2015). Farming salt-tolerant fish in high salinity water enables the utilization of degraded water and optimizes the use of water resources (Food and Agriculture Organization, 2016).

3.25. Recirculating aquaculture systems (RAS)

Recirculating aquaculture systems (Fig. 8) have been recommended as one of the potential measures to develop eco-friendly and sustainable aquaculture while adapting to climate change (Ahmed and Turchini, 2021b). RAS are water-efficient intensive aquaculture systems with high productivity that do not have negative environmental effects like habitat degradation, water pollution and algal blooms, or reduced biodiversity because of species escapes, disease outbreaks, and parasitic transmission (Li et al., 2023; Shitu et al., 2022). Additionally, because RAS is performed in a closed system with controlled environmental conditions, climatic variables like variations in rain, floodings, droughts, global warming, cyclones, salinity fluctuations, ocean acidification, and sea level rise have a minimal impact on their functioning (Ahmed and Turchini, 2021b; Balasubramanian, 2020). RAS contributes to increased efficiency in feed conversion, although, compared to open farming systems, RASs demand higher technical input and consume more energy for water aeration and purification in order to provide the fish with ideal conditions (Bergman et al., 2020).

3.26. Integrated monitoring and notification systems

The development of integrated monitoring systems (e.g. temperature and rain monitoring), risk communication plan, and early notification systems to inform and prepare stakeholders of the fish and seafood sector. An example is the Technological Institute for the Control of the Marine Environment (INTECMAR) monitoring program, which can be readily accessed online and offers alerts and warnings about upcoming red tides and other water conditions important for mussel farms. Routine monitoring and surveillance of aquaculture facilities are especially useful in vulnerable areas to assist farmers and other stakeholders in anticipating weather anomalies and upcoming hazardous events (Reid et al., 2019; Chang et al., 2013; Desilva and Soto, 2009; Poulain et al., 2018).

3.27. Sea level rise adaptation

Upgrading physical protection by building robust infrastructure such as sea walls and groynes and relocating fishing activities away from some low-lying coastal and deltaic zones to areas that are less prone to clime change hazards will be required to protect fish farming operations from rising sea level threats, flood hazards, inundation, storms, and degradation of water quality and infrastructure (Global Adaptation and Resilience to Climate Change and Zolnikov, 2019; Sharaan et al., 2022; Lim-Camacho et al., 2015).

e) Post-production activities resilience strategies

Food and beverage manufacturing companies, researchers, policymakers, and other stakeholders acknowledge the need for the transformation of post-production activities (i.e. food & beverage manufacture, packaging, transport, retail and disposal), to become sustainable and resilient to the changing climate (Galanakis, 2023). Reducing GHG emissions and increasing production can both be accomplished by using energy and resources more efficiently during food & beverage manufacturing, distribution, and retail (Vermeulen et al., 2012). Lowering the carbon emissions of food and beverage processing has a wide range of options, including automation to boost production output while consuming less energy, process optimization to achieve

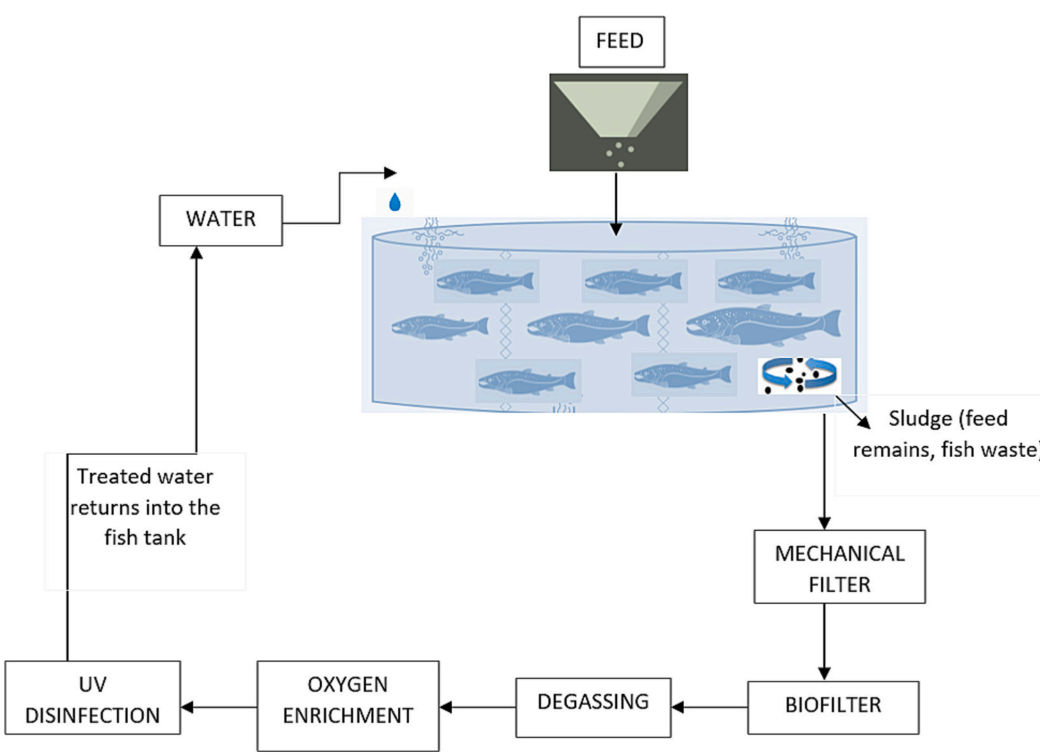

Fig. 8. Schematic diagram of a recirculating aquaculture system.

minimized heating and cooling requirements, minimizing food waste generation, valorisation of food industry waste and by-products, adoption of renewable energy sources, and the development of environmentally friendly packaging (Sovacool et al., 2021). Traditional preservation technologies, like thermal food processing, emit high amounts of GHGs due to their higher energy requirements, whereas green technologies, like non-thermal processing technologies (e.g. high-pressure processing and UV-C technology), have a lower energy requirement and carbon footprint (Hassoun et al., 2022).

Different sectors (i.e. beer manufacture, beverage production, fruit and vegetable processing, etc.) have implemented measures to reduce water consumption in response to decreased water availability. These measures include recovering industrial process water, reusing cooling water, reducing rinsing water quantity for bottle cleaning in beverage manufacturing facilities, steam-peeling fruits and vegetables without the use of cold water to condense water vapor (Valta et al., 2016). The most common sustainable packaging transition strategies include usage of alternative plastic-free materials, the use of reusable, recyclable, or compostable packaging, and banning the use of plastic packaging identified as controversial (e.g. polyvinyl chloride (PVC)) or non-essential (e.g. plastic straws) (Phelan et al., 2022). Furthermore, food and agricultural waste are considered a promising raw materials for producing biodegradable packaging, which can further lead to reducing food waste (Gupta et al., 2022).

According to a United Nations report, if food waste were a country, it would be the world's third largest emitter of GHGs. Food processing firms and grocery stores can offer leftover food and items close to expiration at discount prices for pickup by clients after closing times (Riesenegger and Hübner, 2022). In addition, food deemed unfit for human consumption in the retail sector can be reused for feeding animals in the pig and poultry sectors. Another potential application is the use of discarded food in anaerobic digestion to produce compost and biogas (Halloran et al., 2014).

One adaptation response that can be implemented along the supply chain is to locate farms close to major roadways to ensure easier access to transportation and reduce the risk of inaccessibility to major transportation lines after extreme weather events such as cyclones. Additional recommendations are to install cold storage infrastructure closer to markets and in areas with lower vulnerability to weather extremes and natural hazards, guaranteeing that products can still reach marketplaces (Lim-Camacho et al., 2015). Refrigerated transportation and storage will combat quality deterioration associated with rising temperatures (Parajuli et al., 2019).

(v) Implications of the vulnerability of food supply chains to climate change-induced disruptions for food security, policy, and practice

Reduced food supply due to disruptions in operations along the food chain causes increases in production, processing, distribution, or retail costs that are transferred to the customer and greatly contribute to high food prices (Umar et al., 2017). While some people already struggle to buy food, continuous increases in food prices or a decline in purchasing power could greatly expand the scope and severity of this issue. Moreover, when the population is unable to travel to food procurement points, physical food inaccessibility may follow (Chodur et al., 2018). Food procurement centres such as retail sites might become inaccessible because of the rupture of transportation networks due to extreme weather events. After severe flooding, individuals in some areas might not be able to reach marketplaces and food pantries to source food due to treacherous road conditions. Additionally, flooding can lengthen travel times to food sourcing facilities because people may not be able to use the facilities nearest their houses (Casellas Connors et al., 2022).

In the event of harvest lost or damage to infrastructure like roads or market, a climate catastrophe could indirectly impact individuals and entities that export food to other countries (Harris et al., 2022). The interconnectivity of food trade in the world indicates that climate-related disruptions greatly impact the global food market since countries depend on one another to ensure a sufficient and diverse supply of food. Policy initiatives should concentrate on diversifying trading networks (and food procurement sources) to spread out risk and disperse disruptions as well as investing efforts in striking a balance between increased domestic production resilience and diversified food production and consumption (to reduce dependency on major food crops), while maintaining the effectiveness of international trade (Puma et al., 2015; Schollaert Uz et al., 2019). Losses from climatic events are decreased by local food sourcing and food supply chain shortening. Climate-induced disruptions on roadways result in fewer disturbances and losses when the average distance between the producer/supplier and the buyer is decreased (Colon et al., 2021; Vicente-Vicente et al., 2021).

4. Discussion

4.1. Overview of findings of included studies

The findings of the current study highlighted that the vulnerability of the food supply chain to climatic disruptions is a result of intricate interactions among numerous stakeholders and factors including geographic location, producers, consumers, food procurement points, infrastructure systems (such as roads, retail sites, electrical power generation facilities, and farm facilities), government, scientific community, and insurance (Lunt et al., 2016). This indicates the usefulness of partnerships across industries and sectors to respond to and plan better and more effectively for concurrent food supply chain shocks and failures.

The primary production sector was discussed in several publications (Lennon, 2015; Lunt et al., 2016; Burhan et al., 2017; Elias et al., 2017; Gaupp et al., 2019; Lin et al., 2020; Gerken and Morrison, 2022; Rahman et al., 2022; Tagwi, 2022; Fan et al., 2021b) and was recognized to be the most vulnerable component of the food chain to climatic variations, with several production systems already affected, namely; rice (Wang et al., 2021; Saravanakumar et al., 2022), wheat (Powell et al., 2012; Senapati et al., 2019; Francioli et al., 2021; Wang et al., 2021), potato (Rahman et al., 2022), tomato (Elias et al., 2017), citrus (Fares et al., 2017), black cardamom (Rousseau and Xu, 2021), livestock (Godde et al., 2021; Holechek et al., 2020; Soni et al., 2022; Giridhar and Samireddypalle, 2015; de Vries et al., 2016; Oyas et al., 2018; Tyler et al., 2021) and poultry (Nawaz et al., 2021; Liang et al., 2020; Wasti et al., 2020). This finding is in accordance with those of Malik et al. (2022), stating that the impacts of climate change are noticed in all three of the main production sectors: agriculture, fisheries, and livestock, with the vegetable and livestock industries being the most impacted. Furthermore, the impacts of climate change extend to other food supply chain components, like transportation and consumption (Malik et al., 2022). On the other hand, some models do not predict the negative effects of climate change on the primary production of tuna in the coming decades (Mullon et al., 2017). A variation in the damage caused by climatic hazards was equally observed. This is because each catastrophe is unique and might not present a similar severity and hazard level to other events (Lin et al., 2020). The severity, geographical extent, duration, and timing of climate extremes relative to the food production stage (e.g. crop growth phase or animal rearing stage) affect the shock intensity (Schollaert Uz et al., 2019).

Extreme temperatures and droughts were seen to have pronounced effects on the food supply chain. The drought effects vary among different producers, and in the majority of instances, the lower water supply is responsible for the reduced production capacity of food production and processing (Perdana et al., 2022). The current work highlights the impacts of declines in agricultural output on food prices, labour, food processing activities and associated supply chain activities. Similarly, Bekchanov and Lamers (2016) indicated that reduced farm yields cause a drop in labour demand and capital resources and would result in higher prices of agricultural goods. The reduced farming output would also lead to decreased agrifood processing productivity (Bekchanov and Lamers, 2016). Nevertheless, it was argued that crop failure risk and production loss could be greatly reduced if the increase in global temperatures is limited to 1.5 °C (Gaupp et al., 2019).

Food production and availability are impacted by climate change in many diverse ways, which affects the supply of food. However, agricultural food production activities account for a third of greenhouse gases (GHGs) (Gilbert, 2012). The increased human exploitation of natural resources to meet rising living standards, increasing energy utilization, population growth, and diet changes are all human-induced factors contributing to the climate crisis (Tong et al., 2022; Osman et al., 2023). These factors lead to an increase in emissions of GHGs such as carbon dioxide (CO_2), methane (CH_4), nitrous oxides (N_2O), and water vapor, resulting in higher temperatures referred to as 'global warming' and increased precipitation rates in some regions, causing extreme weather patterns (Binns et al., 2021; Affoh et al., 2022). Due to the growing population and increased demand for food, a significant portion of the world's freshwater resources have been used up, and agricultural production is declining worldwide (Islam et al., 2019). Food shortages and a sharp rise in food inflation have been brought on by a severe fall in agricultural yields and climate-derived obstacles in providing food items across the world (Misra, 2014). Moreover, a rise in stunting and wasting with lower agricultural yields has been observed especially in low- and middle-income nations (Ebi and Loladze, 2019). Three major ways through which climate change and environmental shocks negatively impact food access and availability are a) decreased food production for consumption; b) lower earnings for people who depend on agriculture and natural resources for a living, which reduces their food purchasing power; and c) food price increase and volatility following climate shocks, which lowers the ability to purchase food of individuals who depend on markets to obtain food items (Holleman et al., 2020). Table 4 synthesizes the findings from each stage (production, processing, distribution, consumption) to present a more cohesive picture of the supply chain's overall vulnerability.

This table highlights the interconnectivity and vulnerability of each stage of the food supply chain to climate change. It underscores the need for integrated strategies that address the unique challenges at each stage while ensuring the overall resilience of the food supply chain.

Table 4
Summary of findings of food supply chain stages.

Supply chain stage	Key vulnerabilities	Implications	Potential strategies for resilience
Production	- Elevated temperatures, droughts affecting global food production and yield. - Resource contamination, growing season failure, and farm business failure. - Reduced productivity negatively affecting the food supply.	- Decreased food production capacity. - Impact on industries using agricultural products as raw materials. - Challenges in primary production anticipated to be higher due to climate change.	- Enhanced soil quality and water usage efficiency. - Adoption of climate-resilient crops and improved farming techniques. - Genetic improvement in livestock and crop varieties.
Processing	- Damage to food processing facilities from hazardous events.	- Halting of food processing operations. - Higher food prices contributing to malnutrition and undernutrition.	- Using green and energy-efficient technologies.
	- Disturbed food sourcing mechanisms due to lower availability of agricultural raw materials.	- Potential global increase in deaths due to food insecurity.	- Reduction of water consumption and sustainable packaging. - Implementing non-thermal processing technologies to reduce GHGs.
	- Economic inaccessibility of food and beverages due to higher prices.		
Distribution	- Operational risks due to infrastructure deterioration. - Transportation networks highly vulnerable to climate change	- Disruptions in the constant provision of food along wider supply chains. - Potential inaccessibility to food procurement centers due to extreme weather events.	- Enhanced infrastructure to withstand climatic hazards. - Implementing insurance schemes for farmers.
	-induced natural hazards.		- Developing more efficient integrated monitoring systems.
Consumption	- Decreased availability of nutritious foods. - Increased food prices affecting consumer purchasing power.	- Wider impact on food security and nutrition. - Potential increase in malnutrition, particularly in vulnerable communities.	- Setting up buffer stocks in vulnerable areas. - Building capacity in drought management and planning.
	- Geographical inaccessibility due to extreme weather events disrupting transportation networks.		- Leveraging adaptive governance to enhance food supply stability.

4.2. Limitations and strengths of the study

This review provided details on the food supply chain vulnerabilities associated with climate change and described some negative economic effects in terms of production output, food prices, and welfare changes. This study can improve theory, practice, and policy design by offering a broad and in-depth view based on vulnerability assessment to evaluate various risk factors in the food supply chain and transform food supply chains to better adjust to climate change disturbances.

This scoping review is founded on content analysis. Despite our efforts to reduce subjectivity during the article selection process, it is possible that some bias may still exist. For example, it is possible that some pertinent publications were overlooked because they were either not yet published or were found in databases that were not searched. Additionally, there may have been some selection bias caused by the inclusion and exclusion criteria. For instance, additional relevant articles may have been missed since the search method concentrated primarily on English-language publications. On the other hand, the strength of this review includes the diverse nature of the articles included in this scoping review, that studied different supply chain stages, different food types, and the food supply chain as a whole. The study comprehensively reviewed existing evidence on the impact of climate-related shocks on the food supply chain while considering potential benefits, adaptation/resilience strategies as well as negative impacts. The risks of bias were minimized as all the publications were analysed equally without preference for the publisher/source.

This research represents the first authors' attempt to evaluate the food supply chain vulnerability to climatic variability. Despite efforts to comprehend our changing climate, we are unable to anticipate specific climatic anomalies, particularly on the long-term. It is not yet clear to what extent each dimension of the food supply chain as well each food product from various origins will be impacted by climate change. The food supply chain is composed of interconnected elements that each require in-depth evaluation to better understand the climate-related shocks that might impact the functioning of each individual element in various regions of the world, as well as the supply of various food products on the short-term and long-term.

4.3. Recommendations for future research

It is important to note that the impacts of climate change risks will worsen if nothing is done (Odeku, 2013). Many studies included in the current work explored the vulnerabilities of the production sector and agricultural supply chain to climate change, but fewer studies examined the impacts on food processing, transport, distribution (retail) and consumption. In the animal production sector, a higher number of studies have focused on the seafood sector (Gephart et al., 2017; Mullon et al., 2017; Ragagnin et al., 2018; Brain and Prosser, 2022; Muringai et al., 2022; Robinson et al., 2022; Tran et al., 2022), in comparison to other industries. Regarding the distribution sector, a relatively higher number of studies have been published on access to retail food facilities. However, there has been little investigation into physical access to food pantries to better understand their importance as a food procurement point in the wake of disasters. These gaps need to be filled to improve the readiness of the wider food supply chain for environmental shocks. Another challenge for future research is to understand the relationship between climate change, smallholder farmers' income (especially in sub-Saharan Africa), food supply chain disruptions, nutrition outcomes, and human health (Schnitter and Berry, 2019).

Numerous studies have focused on the reductions in yield while disregarding the cascading effects (physical, social, and economic) that occur further along the supply chain until food consumption and disposal. Despite the fact that there is an increasing number of studies in this field, the impact of climate change on major crops and staple foods such as rice, wheat, and maize have been discussed extensively. More studies into the effects of a variety of unanticipated climatic disruptions are necessary to address the issue of data unavailability regarding various food supply chain types and certain regions of the world, particularly in low- and middle-income countries.

The application of process-based models of supply chain functions such as production, processing, logistics and distribution could account for better predictability of future climatic scenarios as well as their impacts on food supply. It is necessary to document desirable future changes in the food industry in the context of a changing climate to support policy reforms and measures to be undertaken by the stakeholders of the food industry to reach targeted outcomes that are characterized by sustainability to achieve climate change resilience.

There continues to be little quantitative knowledge of the diverse socioeconomic implications (for example, GDP changes, global market dynamics, commodity prices and changes in livelihoods) of climate-induced modifications in food production, provision and consumption in various countries (Wang et al., 2021). There is a need to improve the documentation of climate effects and potential resilience options along the food supply chain to better equip policymakers with information about opportunities and challenges in food security policy formulation. Contingency plans for the worst-case scenarios need to be developed or updated taking into consideration the available natural, human, and capital resources. In low-income nations, much effort needs to be done in view of the huge vulnerability of developing countries.

Furthermore, it was recently argued that industry 4.0 components such as the internet of things (IoT) offer a plethora of solutions through the use of smart sensors and devices to collect real-time information from different stages in the food supply chain, including temperature, quality, transportation data, storage data, and environmental information. IoT sensors enable temperature monitoring at critical control points within cold food supply networks to provide key food safety data (Hassoun et al., 2022). As a result, there is a growing need to explore the potential of industry 4.0 technologies to help with resource efficiency, monitoring, and addressing complex food supply chain issues. To sum up, closing the data gap is critical to addressing the vulnerability of food supply chains to climate change and improving their resilience. This will promote evidence-informed policies and targeted interventions that are sustainable, affordable and effective. This is true for all countries and regions of the world, and even more so for low-income countries.

5. Conclusion

Climate-related events threaten all dimensions of the supply chain of locally produced food and imported foodstuffs, and consequently, food and nutrition security. A higher vulnerability to climate change has been noted in the production sector. As a result, the primary production component of the food supply chain has received much attention. Even though the production end of the chain may merit such consideration, resilience planning is unlikely to be effective unless all food supply chain links are taken into account. According to the current research findings, the effects of climate change on the food supply chain may equally result in reduced welfare levels in society.

Increased awareness of the stressors responsible for climate variability and change is required to effectively address predicted environmental changes. There are possibilities for improvements in the monitoring or modelling of major climate change impacts on the food supply chain to enhance the predictability of climate change. Additional evaluations that closely mimic real-world conditions are required to ameliorate future projections and better the resilience of our global food supply chain to climate change in the upcoming years.

Ensuring the supply of wholesome food in a climate changing world necessitates synergies across sectors to improve urban and rural development planning that takes into account agriculture and food systems, thus fostering an effective supply network linking food producers and markets. Private sector, academics, and governments are required to work together to implement actions that will improve resilience or reduce the vulnerability of the food supply chain to climate change. Such actions include domestic yield improvements, de novo domestication of crops, reduction in GHG emissions, investment in public food buffer stocks, and safeguarding or preservation of primary production zones. Therefore, climate change is a complex issue that requires a multifaceted approach, highlighting the need for further studies focusing specifically on the collaborative dynamics and cooperative strategies within food supply chains in the face of climate change.

Ethics approval and consent to participate

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Consent for publication

All the authors read and agreed to publish this article.

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Rose Daphnee Tchonkouang: Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Helen Onyeaka:** Writing – review & editing, Supervision. **Hugue Nkoutchou:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that support the findings of this article are available within the article. The Zotero report of the 67 papers included in this review is available on GitHub (https://github.com/Rose-Daphnee-Tchonkouang/Foodsup_climate).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.171047.

References

Abisha, R., Krishnani, K.K., Sukhdhane, K., Verma, A.K., Brahmane, M., Chadha, N.K., 2022. Sustainable development of climate-resilient aquaculture and culture-based fisheries through adaptation of abiotic stresses: a review. Journal of Water and Climate Change 13, 2671–2689. https://doi.org/10.2166/wcc.2022.045.

Acevedo, M., Pixley, K., Zinyengere, N., Meng, S., Tufan, H., Cichy, K., Bizikova, L., Isaacs, K., Ghezzi-Kopel, K., Porciello, J., 2020. A scoping review of adoption of climate-resilient crops by small-scale producers in low- and middle-income countries. Nat. Plants 6, 1231–1241. https://doi.org/10.1038/s41477-020-00783-z.

Affoh, R., Zheng, H., Dangui, K., Dissani, B.M., 2022. The impact of climate variability and change on food security in Sub-Saharan Africa: perspective from panel data analysis. Sustainability 14, 759. https://doi.org/10.3390/su14020759.

Agabiirwe, C.N., Dambach, P., Methula, T.C., Phalkey, R.K., 2022. Impact of floods on undernutrition among children under five years of age in low- and middle-income countries: a systematic review. Environmental Health: A Global Access Science Source 21. https://doi.org/10.1186/s12940-022-00910-7.

Ahmed, N., Diana, J.S., 2016. Does climate change matter for freshwater aquaculture in Bangladesh? Reg. Environ. Chang. 16, 1659–1669. https://doi.org/10.1007/s10113-015-0899-6.

Ahmed, N., Turchini, G.M., 2021a. The evolution of the blue-green revolution of rice-fish cultivation for sustainable food production. Sustain. Sci. 16, 1375–1390. https://doi.org/10.1007/s11625-021-00924-z.

Ahmed, N., Turchini, G.M., 2021b. Recirculating aquaculture systems (RAS): environmental solution and climate change adaptation. J. Clean. Prod. 297, 126604 https://doi.org/10.1016/j.jclepro.2021.126604.

Ahmed, T., Scholz, M., Al-Faraj, F., Niaz, W., 2016. Water-related impacts of climate change on agriculture and subsequently on public health: a review for generalists with particular reference to Pakistan. Int. J. Environ. Res. Public Health 13, 1051. https://doi.org/10.3390/ijerph13111051.

Allison, E.H., Perry, A.L., Badjeck, M.-C., Neil Adger, W., Brown, K., Conway, D., Halls, A. S., Pilling, G.M., Reynolds, J.D., Andrew, N.L., et al., 2009. Vulnerability of national economies to the impacts of climate change on fisheries. Fish Fish. 10, 173–196. https://doi.org/10.1111/j.1467-2979.2008.00310.x.

Altaf, I., Rashid, F. ul, Dar, J.A., Rafiq, Mohd, 2015. Vulnerability assessment and patching management. In: Proceedings of the 2015 International Conference on Soft Computing Techniques and Implementations (ICSCTI), pp. 16–21. October.

Andani, A., Irham, I., Jamhari, J., Suryantini, A., 2022. Multifaceted social and environmental disruptions impact on smallholder plantations' resilience in Indonesia. Sci. World J. 2022 https://doi.org/10.1155/2022/6360253.

Antle, J.M., Capalbo, S.M., 2010. Adaptation of agricultural and food systems to climate change: an economic and policy perspective. Appl. Econ. Perspect. Policy 32, 386–416. https://doi.org/10.1093/aepp/ppq015.

Anyamba, A., Chretien, J.-P., Small, J., Tucker, C.J., Formenty, P.B., Richardson, J.H., Britch, S.C., Schnabel, D.C., Erickson, R.L., Linthicum, K.J., 2009. Prediction of a rift valley fever outbreak. Proc. Natl. Acad. Sci. 106, 955–959. https://doi.org/10.1073/pnas.0806490106.

Anzures-Olvera, F., Macías-Cruz, U., Álvarez-Valenzuela, F.D., Correa-Calderón, A., Díaz-Molina, R., Hernández-Rivera, J.A., Avendaño-Reyes, L., 2015. Effect of season (summer vs. winter) on physiological variables, milk production and antioxidant capacity of Holstein cows in an arid zone of northwestern Mexico. Archivos de medicina veterinaria 47, 15–20. https://doi.org/10.4067/S0301-732X2015000100004.

Armah, F.A., Odoi, J.O., Yengoh, G.T., Obiri, S., Yawson, D.O., Afrifa, E.K.A., 2011. Food security and climate change in drought-sensitive savanna zones of Ghana. Mitig. Adapt. Strateg. Glob. Chang. 16, 291–306. https://doi.org/10.1007/s11027-010-9263-9.

Arneth, A., Shin, Y.-J., Leadley, P., Rondinini, C., Bukvareva, E., Kolb, M., Midgley, G.F., Oberdorff, T., Palomo, I., Saito, O., 2020. Post-2020 biodiversity targets need to embrace climate change. Proc. Natl. Acad. Sci. 117, 30882–30891. https://doi.org/10.1073/pnas.2009584117.

Assess Vulnerability & Risk, 2023. U.S. Climate Resilience Toolkit. Available online: https://toolkit.climate.gov/steps-to-resilience/assess-vulnerability-risk. accessed on 24 February.

Athrey, G., 2020. Chapter 18 - poultry genetics and breeding. In: Bazer, F.W., Lamb, G.C., Wu, G. (Eds.), Animal Agriculture. Academic Press, pp. 317–330. ISBN 978-0-12-817052-6.

Baca, M., Läderach, P., Haggar, J., Schroth, G., Ovalle, O., 2014. An integrated framework for assessing vulnerability to climate change and developing adaptation strategies for coffee growing families in Mesoamerica. PLoS One 9, e88463. https://doi.org/10.1371/journal.pone.0088463.

Bakala, H.S., Singh, G., Srivastava, P., Bakala, H.S., Singh, G., Srivastava, P., 2020. Smart Breeding for Climate Resilient Agriculture. IntechOpen (ISBN 978-1-83968-310-7.).

Balasubramanian, C.P., 2020. Recirculating Aquaculture System Concepts and Designs.

Baldos, U.L.C., Hertel, T.W., 2015. The role of international trade in managing food security risks from climate change. Food Secur. 7, 275–290. https://doi.org/10.1007/s12571-015-0435-z.

Barton, L., Murphy, D.V., Butterbach-Bahl, K., 2013. Influence of crop rotation and liming on greenhouse gas emissions from a semi-arid soil. Agric. Ecosyst. Environ. 167, 23–32. https://doi.org/10.1016/j.agee.2013.01.003.

Baum, S.D., Denkenberger, D.C., Pearce, J.M., Robock, A., Winkler, R., 2015. Resilience to global food supply catastrophes. Environ. Syst. Decis. 35, 301–313. https://doi.org/10.1007/s10669-015-9549-2.

Bekchanov, M., Lamers, J.P.A., 2016. Economic costs of reduced irrigation water availability in Uzbekistan (Central Asia). Reg. Environ. Chang. 16, 2369–2387. https://doi.org/10.1007/s10113-016-0961-z.

Berger, J., Wangchuk, T., Briceño, C., Vila, A., Lambert, J.E., 2020. Disassembled food webs and messy projections: modern ungulate communities in the face of unabating human population growth. Front. Ecol. Evol. 8 https://doi.org/10.3389/fevo.2020.00128.

Bergman, K., Henriksson, P.J.G., Hornborg, S., Troell, M., Borthwick, L., Jonell, M., Philis, G., Ziegler, F., 2020. Recirculating aquaculture is possible without major energy tradeoff: life cycle assessment of warmwater fish farming in Sweden. Environ. Sci. Technol. 54, 16062–16070. https://doi.org/10.1021/acs.est.0c01100.

Bernabucci, U., 2019. Climate change: impact on livestock and how can we adapt. Anim. Front. 9, 3–5. https://doi.org/10.1093/af/vfy039.

Binns, C.W., Lee, M.K., Maycock, B., Torheim, L.E., Nanishi, K., Duong, D.T.T., 2021. Climate change, food supply, and dietary guidelines. Annu. Rev. Public Health 42, 233–255. https://doi.org/10.1146/annurev-publhealth-012420-105044.

Bottero, M., 2011. Indicators assessment systems. In: Cassatella, C., Peano, A. (Eds.), Landscape Indicators: Assessing and Monitoring Landscape Quality. Springer Netherlands, Dordrecht, pp. 15–29. ISBN 978-94-007-0366-7.

Brain, R.A., Prosser, R.S., 2022. Human induced fish declines in North America, how do agricultural pesticides compare to other drivers? Environ. Sci. Pollut. Res. 29, 66010–66040. https://doi.org/10.1007/s11356-022-22102-z.

Bryndum-Buchholz, A., Tittensor, D.P., Lotze, H.K., 2021. The status of climate change adaptation in fisheries management: policy, legislation and implementation. Fish Fish. 22, 1248–1273. https://doi.org/10.1111/faf.12586.

Burhan, A., Rasul, G., Qadir, T., Hussain, S., Saqib, M., Bukhari, S.A.A., 2017. Environmental policies to protect pollinators: attributes and actions needed to avert climate borne crisis of oil seed agriculture in Pakistan. AIMS Agriculture and Food 2, 233–250. https://doi.org/10.3934/agrfood.2017.3.233.

Callaway, R., Shinn, A.P., Grenfell, S.E., Bron, J.E., Burnell, G., Cook, E.J., Crumlish, M., Culloty, S., Davidson, K., Ellis, R.P., et al., 2012. Review of climate change impacts on marine aquaculture in the UK and Ireland. Aquat. Conserv. Mar. Freshwat. Ecosyst. 22, 389–421. https://doi.org/10.1002/aqc.2247.

Campbell, B.M., Vermeulen, S.J., Aggarwal, P.K., Corner-Dolloff, C., Girvetz, E., Loboguerrero, A.M., Ramirez-Villegas, J., Rosenstock, T., Sebastian, L., Thornton, P. K., et al., 2016. Reducing risks to food security from climate change. Glob. Food Sec. 11, 34–43. https://doi.org/10.1016/j.gfs.2016.06.002.

Carabaño, M.J., Ramón, M., Menéndez-Buxadera, A., Molina, A., Díaz, C., 2019. Selecting for heat tolerance. Anim Front 9, 62–68. https://doi.org/10.1093/af/vfy033.

Casellas Connors, J.P., Safayet, M., Rosenheim, N., Watson, M., 2022. Assessing changes in food pantry access after extreme events. Agric. Hum. Values. https://doi.org/10.1007/s10460-022-10373-8.

Chae, B.J., 2000. Impacts of wet feeding of diets on growth and carcass traits in pigs. J. Appl. Anim. Res. 17, 81–96. https://doi.org/10.1080/09712119.2000.9706293.

Chang, Y., Lee, M.-A., Lee, K.-T., Shao, K.-T., 2013. Adaptation of fisheries and mariculture management to extreme oceanic environmental changes and climate variability in Taiwan. Mar. Policy 38, 476–482. https://doi.org/10.1016/j.marpol.2012.08.002.

Chari, F., Ngcamu, B.S., 2017. An assessment of the impact of disaster risks on dairy supply chain performance in Zimbabwe. Cogent Engineering 4. https://doi.org/10.1080/23311916.2017.1409389.

Chari, F., Ngcamu, B.S., 2022. Climate change and its impact on urban agriculture in Sub-Saharan Africa: a literature review. Environmental & Socio-economic Studies 10, 22–32. https://doi.org/10.2478/environ-2022-0014.

Chodur, G.M., Zhao, X., Biehl, E., Mitrani-Reiser, J., Neff, R., 2018. Assessing food system vulnerabilities: a fault tree modeling approach. BMC Public Health 18. https://doi.org/10.1186/s12889-018-5563-x.

Climate Adapt Impacts, Risks and Vulnerabilities — English, 2023. Available online. https://climate-adapt.eea.europa.eu/en/knowledge/adaptation-information/vulnerabilities-and-risks. accessed on 23 February.

Climate Change Quantitative Vulnerability Assessments, 2023. Thought Leadership | Exponent. Available online: https://www.exponent.com/knowledge/thought-leadership/2023/02/quantitative-climate-change-vulnerability/?pageSize=NaN&pageNum=0&loadAllByPageSize=true. accessed on 24 February.

Codjoe, S.N.A., Owusu, G., 2011. Climate change/variability and food systems: evidence from the Afram Plains, Ghana. Reg. Environ. Chang. 11, 753–765. https://doi.org/10.1007/s10113-011-0211-3.

Colon, C., Hallegatte, S., Rozenberg, J., 2021. Criticality analysis of a country's transport network via an agent-based supply chain model. Nature Sustainability 4, 209–215. https://doi.org/10.1038/s41893-020-00649-4.

Cooney, R., de Sousa, D.B., Fernández-Ríos, A., Mellett, S., Rowan, N., Morse, A.P., Hayes, M., Laso, J., Regueiro, L., Wan, A.H., et al., 2023. A circular economy framework for seafood waste valorisation to meet challenges and opportunities for intensive production and sustainability. J. Clean. Prod. 392 https://doi.org/10.1016/j.jclepro.2023.136283.
Dargin, J., Berk, A., Mostafavi, A., 2020. Assessment of household-level food-energy-water nexus vulnerability during disasters. Sustain. Cities Soc. 62 https://doi.org/10.1016/j.scs.2020.102366.
Das, I., Lauria, V., Kay, S., Cazcarro, I., Arto, I., Fernandes, J.A., Hazra, S., 2020. Effects of climate change and management policies on marine fisheries productivity in the north-east coast of India. Sci. Total Environ. 724, 138082 https://doi.org/10.1016/j.scitotenv.2020.138082.
Daszkiewicz, T., 2022. Food production in the context of global developmental challenges. Agriculture (Switzerland) 12. https://doi.org/10.3390/agriculture12060832.
Davis, K.F., Downs, S., Gephart, J.A., 2021. Towards food supply chain resilience to environmental shocks. Nat Food 2, 54–65. https://doi.org/10.1038/s43016-020-00196-3.
Desilva, S., Soto, D., 2009. Climate change and aquaculture: potential impacts. In: Cochrane, K., De Young, C., Soto, D., Bahri, T. (Eds.), Adaptation and Mitigation in Climate Change Implications for Fisheries and Aquaculture: Overview of Current Scientific Knowledge. FAO Fisheries and Aquaculture Technical Paper. No. 530. FAO, Rome, pp. 151–212.
Dey, M.M., Gosh, K., Valmonte-Santos, R., Rosegrant, M.W., Chen, O.L., 2016. Economic impact of climate change and climate change adaptation strategies for fisheries sector in Solomon Islands: implication for food security. Mar. Policy 67, 171–178. https://doi.org/10.1016/j.marpol.2016.01.004.
Dhankher, O.P., Foyer, C.H., 2018. Climate resilient crops for improving global food security and safety. Plant Cell Environ. 41, 877–884. https://doi.org/10.1111/pce.13207.
Dong, S., Shang, Z., Gao, J., Boone, R.B., 2020. Enhancing sustainability of grassland ecosystems through ecological restoration and grazing management in an era of climate change on Qinghai-Tibetan Plateau. Agric. Ecosyst. Environ. 287, 106684 https://doi.org/10.1016/j.agee.2019.106684.
Ebi, K.L., Loladze, I., 2019. Elevated atmospheric CO2 concentrations and climate change will affect our Food's quality and quantity. The Lancet Planetary Health 3, e283–e284. https://doi.org/10.1016/S2542-5196(19)30108-1.
Elbasiouny, H., El-Ramady, H., Elbehiry, F., Rajput, V.D., Minkina, T., Mandzhieva, S., 2022. Plant nutrition under climate change and soil carbon sequestration. Sustainability 14, 914. https://doi.org/10.3390/su14020914.
Elias, M.A.S., Borges, F.J.A., Bergamini, L.L., Franceschinelli, E.V., Sujii, E.R., 2017. Climate change threatens pollination services in tomato crops in Brazil. Agric. Ecosyst. Environ. 239, 257–264. https://doi.org/10.1016/j.agee.2017.01.026.
Emadodin, I., Reinsch, T., Taube, F., 2019. Drought and desertification in Iran. Hydrology 6, 66. https://doi.org/10.3390/hydrology6030066.
Ercin, E., Veldkamp, T.I.E., Hunink, J., 2021. Cross-border climate vulnerabilities of the European Union to drought. Nat. Commun. 12 https://doi.org/10.1038/s41467-021-23584-0.
Falloon, P., Bebber, D.P., Dalin, C., Ingram, J., Mitchell, D., Hartley, T.N., Johnes, P.J., Newbold, T., Challinor, A.J., Finch, J., et al., 2022. What do changing weather and climate shocks and stresses mean for the UK food system? Environ. Res. Lett. 17 https://doi.org/10.1088/1748-9326/ac68f9.
Fan, S., Cho, E.E., Meng, T., Rue, C., 2021a. How to prevent and cope with coincidence of risks to the global food system. Annu. Rev. Environ. Resour. 46, 601–623. https://doi.org/10.1146/annurev-environ-012220-020844.
Fan, X., Nan, Z., Ma, Y., Zhang, Y., Han, F., 2021b. Research on the Spatio-temporal impacts of environmental factors on the fresh agricultural product supply chain and the spatial differentiation issue—an empirical research on 31 Chinese provinces. Int. J. Environ. Res. Public Health 18. https://doi.org/10.3390/ijerph182212141.
Fares, A., Bayabil, H.K., Zekri, M., Mattos, D., Awal, R., 2017. Potential climate change impacts on citrus water requirement across major producing areas in the world. Journal of Water and Climate Change 8, 576–592. https://doi.org/10.2166/wcc.2017.182.
Farooq, M.S., Uzair, M., Raza, A., Habib, M., Xu, Y., Yousuf, M., Yang, S.H., Ramzan Khan, M., 2022. Uncovering the research gaps to alleviate the negative impacts of climate change on food security: a review. Front. Plant Sci. 13 https://doi.org/10.3389/fpls.2022.927535.
Fedick, S.L., Santiago, L.S., 2022. Large variation in availability of Maya food plant sources during ancient droughts. Proc. Natl. Acad. Sci. USA 119. https://doi.org/10.1073/pnas.2115657118.
Feindouno, S., 2018. Structural Vulnerability and Fragility: An Assessment Based on Composite Indicators.
Feng, A., Chao, Q., 2020. An overview of assessment methods and analysis for climate change risk in China. Physics and Chemistry of the Earth, Parts A/B/C 117, 102861. https://doi.org/10.1016/j.pce.2020.102861.
Fernández, F.J., Muñoz, M., Ponce Oliva, R.D., Vásquez-Lavín, F., Gelcich, S., 2023. Mapping firms' adaptive profiles: the role of experiences and risk perception in the aquaculture industry. Aquaculture 562. https://doi.org/10.1016/j.aquaculture.2022.738802.
Fernie, A.R., Yan, J., 2019. De novo domestication: an alternative route toward new crops for the future. Mol. Plant 12, 615–631. https://doi.org/10.1016/j.molp.2019.03.016.
Filho, W.L., Setti, A.F.F., Azeiteiro, U.M., Lokupitiya, E., Donkor, F.K., Etim, N.N., Matandirotya, N., Olooto, F.M., Sharifi, A., Nagy, G.J., et al., 2022. An overview of the interactions between food production and climate change. Sci. Total Environ. 838, 156438 https://doi.org/10.1016/j.scitotenv.2022.156438.
Fleming, A., Hobday, A.J., Farmery, A., van Putten, E.I., Pecl, G.T., Green, B.S., Lim-Camacho, L., 2014. Climate change risks and adaptation options across Australian seafood supply chains - a preliminary assessment. Clim. Risk Manag. 1, 39–50. https://doi.org/10.1016/j.crm.2013.12.003.
Food and Agriculture Organization, 2016. Coping With Water Scarcity in Agriculture: A Global Framework for Action in a Changing Climate.
Francioli, D., Cid, G., Kanukollu, S., Ulrich, A., Hajirezaei, M.-R., Kolb, S., 2021. Flooding causes dramatic compositional shifts and depletion of putative beneficial bacteria on the spring wheat microbiota. Front. Microbiol. 12 https://doi.org/10.3389/fmicb.2021.773116.
Fritzsche, K., Schneiderbauer, S., Bubeck, P., Kienberger, S., Buth, M., Zebisch, M., Kahlenborn, W., 2014. The Vulnerability Sourcebook: Concept and Guidelines for Standardised Vulnerability Assessments.
Galanakis, C.M., 2023. The "vertigo" of the food sector within the triangle of climate change, the post-pandemic world, and the Russian-Ukrainian war. Foods 12, 721. https://doi.org/10.3390/foods12040721.
Gaupp, F., Hall, J., Mitchell, D., Dadson, S., 2019. Increasing risks of multiple breadbasket failure under 1.5 and 2 °C global warming. Agric. Syst. 175, 34–45. https://doi.org/10.1016/j.agsy.2019.05.010.
Gautam, P., Kumar, S., Lokhandwala, S., 2019. Chapter 11 - energy-aware intelligence in megacities. In: Kumar, S., Kumar, R., Pandey, A. (Eds.), Current Developments in Biotechnology and Bioengineering. Elsevier, pp. 211–238. ISBN 978-0-444-64083-3.
Geng, Y., Chen, W., Liu, Z., Chiu, A.S.F., Han, W., Liu, Z., Zhong, S., Qian, Y., You, W., Cui, X., 2017. A bibliometric review: energy consumption and greenhouse gas emissions in the residential sector. J. Clean. Prod. 159, 301–316. https://doi.org/10.1016/j.jclepro.2017.05.091.
Gephart, J.A., Deutsch, L., Pace, M.L., Troell, M., Seekell, D.A., 2017. Shocks to fish production: identification, trends, and consequences. Glob. Environ. Chang. 42, 24–32. https://doi.org/10.1016/j.gloenvcha.2016.11.003.
Gerken, A.R., Morrison, W.R., 2022. Pest management in the postharvest agricultural supply chain under climate change. Frontiers in Agronomy 4. https://doi.org/10.3389/fagro.2022.918845.
Ghadge, A., Wurtmann, H., Seuring, S., 2020. Managing climate change risks in global supply chains: a review and research agenda. Int. J. Prod. Res. 58, 44–64. https://doi.org/10.1080/00207543.2019.1629670.
Giannini, T.C., Costa, W.F., Cordeiro, G.D., Imperatriz-Fonseca, V.L., Saraiva, A.M., Biesmeijer, J., Garibaldi, L.A., 2017. Projected climate change threatens pollinators and crop production in Brazil. PLoS One 12. https://doi.org/10.1371/journal.pone.0182274.
Gilbert, N., 2012. One-third of our greenhouse gas emissions come from agriculture. Nature. https://doi.org/10.1038/nature.2012.11708.
Giridhar, K., Samireddypalle, A., 2015. Impact of climate change on forage availability for livestock. In: Sejian, V., Gaughan, J., Baumgard, L., Prasad, C. (Eds.), Climate Change Impact on Livestock: Adaptation and Mitigation. Springer India, New Delhi, pp. 97–112. ISBN 978-81-322-2265-1.
Gjedrem, T., 2015. Disease resistant fish and shellfish are within reach: a review. Journal of Marine Science and Engineering 3, 146–153. https://doi.org/10.3390/jmse3010146.
Global Adaptation and Resilience to Climate Change, 2019. In: Zolnikov, T.R. (Ed.), Palgrave Studies in Climate Resilient Societies. Springer International Publishing, Cham (ISBN 978-3-030-01212-0).
Godber, O.F., Wall, R., 2014. Livestock and food security: vulnerability to population growth and climate change. Glob. Chang. Biol. 20, 3092–3102. https://doi.org/10.1111/gcb.12589.
Godde, C.M., Mason-D'Croz, D., Mayberry, D.E., Thornton, P.K., Herrero, M., 2021. Impacts of climate change on the livestock food supply chain; a review of the evidence. Global Food Secur. 28, 100488 https://doi.org/10.1016/j.gfs.2020.100488.
Gomera, P.M., Mafini, C., 2020. Supply chain management enablers, barriers and disruptions in the animal feed industry in the Western Cape Province of South Africa. Journal of Transport and Supply Chain Management 14, 1–12. https://doi.org/10.4102/jtscm.v14i0.510.
Gómez Murciano, M., Liu, Y., Ünal, V., Sánchez LIzaso, J.L., 2021. Comparative analysis of the social vulnerability assessment to climate change applied to fisheries from Spain and Turkey. Sci. Rep. 11, 13949. https://doi.org/10.1038/s41598-021-93165-0.
Gomez-Zavaglia, A., Mejuto, J.C., Simal-Gandara, J., 2020. Mitigation of emerging implications of climate change on food production systems. Food Res. Int. 134, 109256 https://doi.org/10.1016/j.foodres.2020.109256.
Govindan, R., Al-Ansari, T., 2019. Computational decision framework for enhancing resilience of the energy, water and food nexus in risky environments. Renew. Sust. Energ. Rev. 112, 653–668. https://doi.org/10.1016/j.rser.2019.06.015.
Grigatti, M., Barbanti, L., Hassan, M.U., Ciavatta, C., 2020. Fertilizing potential and CO2 emissions following the utilization of fresh and composted food-waste anaerobic digestates. Sci. Total Environ. 698, 134198 https://doi.org/10.1016/j.scitotenv.2019.134198.
Gross, A., Glaser, B., 2021. Meta-analysis on how manure application changes soil organic carbon storage. Sci. Rep. 11, 5516. https://doi.org/10.1038/s41598-021-82739-7.
Guo, H., Zhang, X., Lian, F., Gao, Y., Lin, D., Wang, J., 2016. Drought risk assessment based on vulnerability surfaces: a case study of maize. Sustainability 8, 813. https://doi.org/10.3390/su8080813.
Guo, H., Wang, R., Garfin, G.M., Zhang, A., Lin, D., Liang, Q., Wang, J., 2021. Rice drought risk assessment under climate change: based on physical vulnerability a quantitative assessment method. Sci. Total Environ. 751, 141481 https://doi.org/10.1016/j.scitotenv.2020.141481.

Gupta, P., Toksha, B., Rahaman, M., 2022. A review on biodegradable packaging films from vegetative and food waste. Chem. Rec. 22, e202100326 https://doi.org/10.1002/tcr.202100326.
Gustafson, D., Asseng, S., Kruse, J., Thoma, G., Guan, K., Hoogenboom, G., Matlock, M., McLean, M., Parajuli, R., Rajagopalan, K., et al., 2021. Supply chains for processed potato and tomato products in the United States will have enhanced resilience with planting adaptation strategies. Nat Food 2, 862–872. https://doi.org/10.1038/s43016-021-00383-w.
Halloran, A., Clement, J., Kornum, N., Bucatariu, C., Magid, J., 2014. Addressing food waste reduction in Denmark. Food Policy 49, 294–301. https://doi.org/10.1016/j.foodpol.2014.09.005.
Hammami, H., Vandenplas, J., Vanrobays, M.-L., Rekik, B., Bastin, C., Gengler, N., 2015. Genetic analysis of heat stress effects on yield traits, udder health, and fatty acids of Walloon Holstein cows. J. Dairy Sci. 98, 4956–4968. https://doi.org/10.3168/jds.2014-9148.
Hanson, B., May, D., 2010. Salinity Control With Drip Irrigation. January 1, Vol. 2.
Harris, F., Amarnath, G., Joy, E.J., Dangour, A.D., Green, R.F., 2022. Climate-related hazards and Indian food supply: assessing the risk using recent historical data. Global Food Security 33. https://doi.org/10.1016/j.gfs.2022.100625.
Harvey, C.A., Rakotobe, Z.L., Rao, N.S., Dave, R., Razafimahatratra, H., Rabarijohn, R.H., Rajaofara, H., MacKinnon, J.L., 2014. Extreme vulnerability of smallholder farmers to agricultural risks and climate change in Madagascar. Philos. Trans. R. Soc. B 369, 20130089. https://doi.org/10.1098/rstb.2013.0089.
Hassoun, A., Prieto, M.A., Carpena, M., Bouzembrak, Y., Marvin, H.J.P., Pallarés, N., Barba, F.J., Punia Bangar, S., Chaudhary, V., Ibrahim, S., et al., 2022. Exploring the role of green and industry 4.0 technologies in achieving sustainable development goals in food sectors. Food Res. Int. 162 https://doi.org/10.1016/j.foodres.2022.112068.
Hecht, A.A., Biehl, E., Barnett, D.J., Neff, R.A., 2019. Urban food supply chain resilience for crises threatening food security: a qualitative study. J. Acad. Nutr. Diet. 119, 211–224. https://doi.org/10.1016/j.jand.2018.09.001.
Hoffmann, E., Schöpflin, P., 2022. Climate change risk assessment and adaptation measures in the food supply chain—perceptions and responses of buying firms. In: Leal Filho, W., Djekic, I., Smetana, S., Kovaleva, M. (Eds.), Handbook of Climate Change Across the Food Supply Chain. Springer International Publishing, Cham, pp. 285–304. Climate Change Management. ISBN 978-3-030-87934-1.
Holechek, J.L., Geli, H.M.E., Cibils, A.F., Sawalhah, M.N., 2020. Climate change, rangelands, and sustainability of ranching in the Western United States. Sustainability 12, 4942. https://doi.org/10.3390/su12124942.
Holleman, C., Rembold, F., Crespo, O., Conti, V., 2020. The Impact of Climate Variability and Extremes on Agriculture and Food Security - An Analysis of the Evidence and Case Studies: Background Paper for the State of Food Security and Nutrition in the World 2018; FAO Agricultural Development Economics Technical Study: Rome (ISBN 978-92-5-133718-9.).
Houston, R.D., Bean, T.P., Macqueen, D.J., Gundappa, M.K., Jin, Y.H., Jenkins, T.L., Selly, S.L.C., Martin, S.A.M., Stevens, J.R., Santos, E.M., et al., 2020. Harnessing genomics to fast-track genetic improvement in aquaculture. Nat. Rev. Genet. 21, 389–409. https://doi.org/10.1038/s41576-020-0227-y.
Hristov, A.N., Degaetano, A.T., Rotz, C.A., Hoberg, E., Skinner, R.H., Felix, T., Li, H., Patterson, P.H., Roth, G., Hall, M., et al., 2018. Climate change effects on livestock in the northeast US and strategies for adaptation. Clim. Chang. 146, 33–45. https://doi.org/10.1007/s10584-017-2023-z.
Intergovernmental Panel on Climate Change Climate Change and Land, 2022. IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems, 1st ed. Cambridge University Press (ISBN 978-1-00-915798-8.).
Islam, S.M.F., Karim, Z., Islam, S.M.F., Karim, Z., 2019. World's demand for food and water: the consequences of climate change. In: Desalination - Challenges and Opportunities. IntechOpen (ISBN 978-1-78984-739-0).
James, T.K., Merfield, C.N., 2021. Weed and soil management: a balancing act☆. In: Reference Module in Earth Systems and Environmental Sciences. Elsevier. ISBN 978-0-12-409548-9.
Kao, Y.-C., Adlerstein, S.A., Rutherford, E.S., 2016. Assessment of top-down and bottom-up controls on the collapse of alewives (Alosa pseudoharengus) in Lake Huron. Ecosystems 19, 803–831. https://doi.org/10.1007/s10021-016-9969-y.
Kazemi Shariat Panahi, H., Dehhaghi, M., Guillemin, G.J., Gupta, V.K., Lam, S.S., Aghbashlo, M., Tabatabaei, M., 2022. Bioethanol production from food wastes rich in carbohydrates. Curr. Opin. Food Sci. 43, 71–81. https://doi.org/10.1016/j.cofs.2021.11.001.
Kingwell, R., Payne, B., 2020. Projected impacts of climate change on farm business risk in three regions of Western Australia. Australian Farm Business Management Journal 12, 32–50. https://doi.org/10.3316/informit.557709167545770.
Kirezieva, K., Jacxsens, L., van Boekel, M.A.J.S., Luning, P.A., 2015. Towards strategies to adapt to pressures on safety of fresh produce due to climate change. Food Res. Int. 68, 94–107. https://doi.org/10.1016/j.foodres.2014.05.077.
Kumar, S., 2011. Composting of municipal solid waste. Crit. Rev. Biotechnol. 31, 112–136. https://doi.org/10.3109/07388551.2010.492207.
Lam, V., Cheung, W., Swartz, W., Sumaila, U., 2012. Climate change impacts on fisheries in West Africa: implications for economic, food and nutritional security. Afr. J. Mar. Sci. 34, 103–117. https://doi.org/10.2989/1814232X.2012.673294.
Lassa, J.A., Teng, P., Caballero-Anthony, M., Shrestha, M., 2019. Revisiting emergency food reserve policy and practice under disaster and extreme climate events. Int. J. Disaster Risk Sci. 10, 1–13. https://doi.org/10.1007/s13753-018-0200-y.
Lebot, V., 2013. Coping with insularity: the need for crop genetic improvement to strengthen adaptation to climatic change and food security in the Pacific. Environ. Dev. Sustain. 15, 1405–1423. https://doi.org/10.1007/s10668-013-9445-1.
Lengnick, L., 2015. The vulnerability of the US food system to climate change. J. Environ. Stud. Sci. 5, 348–361. https://doi.org/10.1007/s13412-015-0290-4.
Lennon, J.J., 2015. Potential impacts of climate change on agriculture and food safety within the island of Ireland. Trends Food Sci. Technol. 44, 1–10. https://doi.org/10.1016/j.tifs.2014.07.003.
Lennox, E., 2015. Double exposure to climate change and globalization in a Peruvian highland community. Soc. Nat. Resour. 28, 781–796. https://doi.org/10.1080/08941920.2015.1024364.
Leonhardt, S.D., Gallai, N., Garibaldi, L.A., Kuhlmann, M., Klein, A.-M., 2013. Economic gain, stability of pollination and bee diversity decrease from southern to northern Europe. Basic and Applied Ecology 14, 461–471. https://doi.org/10.1016/j.baae.2013.06.003.
Li, H., Cui, Z., Cui, H., Bai, Y., Yin, Z., Qu, K., 2023. A review of influencing factors on a recirculating aquaculture system: environmental conditions, feeding strategies, and disinfection methods. J. World Aquacult. Soc. 54, 566–602. https://doi.org/10.1111/jwas.12976.
Li, Y., Xiong, W., Hu, W., Berry, P., Ju, H., Lin, E., Wang, W., Li, K., Pan, J., 2015. Integrated assessment of China's agricultural vulnerability to climate change: a multi-indicator approach. Clim. Chang. 128, 355–366. https://doi.org/10.1007/s10584-014-1165-5.
Liang, Y., Tabler, G.T., Dridi, S., 2020. Sprinkler technology improves broiler production sustainability: from stress alleviation to water usage conservation: a mini review. Frontiers in Veterinary Science 7.
Limbu, S.M., Shoko, A.P., Lamtane, H.A., Kishe-Machumu, M.A., Joram, M.C., Mbonde, A.S., Mgana, H.F., Mgaya, Y.D., 2017. Fish polyculture system integrated with vegetable farming improves yield and economic benefits of small-scale farmers. Aquac. Res. 48, 3631–3644. https://doi.org/10.1111/are.13188.
Lim-Camacho, L., Hobday, A.J., Bustamante, R.H., Farmery, A., Fleming, A., Frusher, S., Green, B.S., Norman-López, A., Pecl, G.T., Plagányi, É.E., et al., 2015. Facing the wave of change: stakeholder perspectives on climate adaptation for Australian seafood supply chains. Reg. Environ. Chang. 15, 595–606. https://doi.org/10.1007/s10113-014-0670-4.
Lin, H.-C., Chou, L.-C., Zhang, W.-H., 2020. Cross-strait climate change and agricultural product loss. Environ. Sci. Pollut. Res. 27, 12908–12921. https://doi.org/10.1007/s11356-019-05166-2.
Lin, L., Xu, F., Ge, X., Li, Y., 2018. Improving the sustainability of organic waste management practices in the food-energy-water Nexus: a comparative review of anaerobic digestion and composting. Renew. Sust. Energ. Rev. 89, 151–167. https://doi.org/10.1016/j.rser.2018.03.025.
Liu, M., Xu, X., Jiang, Y., Huang, Q., Huo, Z., Liu, L., Huang, G., 2020. Responses of crop growth and water productivity to climate change and agricultural water-saving in arid region. Sci. Total Environ. 703, 134621 https://doi.org/10.1016/j.scitotenv.2019.134621.
Lunt, T., Jones, A.W., Mulhern, W.S., Lezaks, D.P.M., Jahn, M.M., 2016. Vulnerabilities to agricultural production shocks: an extreme, plausible scenario for assessment of risk for the insurance sector. Clim. Risk Manag. 13, 1–9. https://doi.org/10.1016/j.crm.2016.05.001.
Mahama, G.Y., Prasad, P.V.V., Roozeboom, K.L., Nippert, J.B., Rice, C.W., 2020. Reduction of nitrogen fertilizer requirements and nitrous oxide emissions using legume cover crops in a no-tillage sorghum production system. Sustainability 12, 4403. https://doi.org/10.3390/su12114403.
Malik, A., Li, M., Lenzen, M., Fry, J., Liyanapathirana, N., Beyer, K., Boylan, S., Lee, A., Raubenheimer, D., Geschke, A., et al., 2022. Impacts of climate change and extreme weather on food supply chains cascade across sectors and regions in Australia. Nat Food 3, 631–643. https://doi.org/10.1038/s43016-022-00570-3.
Mary, P., Ramasamy, M., Jeyamani, R., Shanmugasundaram, R., Sadhanandham, K., Srirangarayan, R., 2020. Saline Soil Reclamation.
Mason, J.G., Eurich, J.G., Lau, J.D., Battista, W., Free, C.M., Mills, K.E., Tokunaga, K., Zhao, L.Z., Dickey-Collas, M., Valle, M., et al., 2022. Attributes of climate resilience in fisheries: from theory to practice. Fish Fish. 23, 522–544. https://doi.org/10.1111/faf.12630.
Matsuda, T., Yano, J., Hirai, Y., Sakai, S., 2012. Life-cycle greenhouse gas inventory analysis of household waste management and food waste reduction activities in Kyoto, Japan. Int. J. Life Cycle Assess. 17, 743–752. https://doi.org/10.1007/s11367-012-0400-4.
Mbow, C., Smith, P., Skole, D., Duguma, L., Bustamante, M., 2014. Achieving mitigation and adaptation to climate change through sustainable agroforestry practices in Africa. Curr. Opin. Environ. Sustain. 6, 8–14. https://doi.org/10.1016/j.cosust.2013.09.002.
McMaster, G.S., Ascough, J.C., Edmunds, D.A., Wagner, L.E., Fox, F.A., DeJonge, K.C., Hansen, N.C., 2014. Simulating unstressed crop development and growth using the unified plant growth model (UPGM). Environ. Model. Assess. 19, 407–424. https://doi.org/10.1007/s10666-014-9402-x.
Medina Litardo, R.C., García Bendezú, S.J., Carrillo Zenteno, M.D., Pérez-Almeida, I.B., Parismoreno, L.L., Lombeida García, E.D., 2022. Effect of mineral and organic amendments on Rice growth and yield in saline soils. J. Saudi Soc. Agric. Sci. 21, 29–37. https://doi.org/10.1016/j.jssas.2021.06.015.
Miao, W., Yuan, X., 2007. The carp farming industry in China - an overview. In: Species and System Selection for Sustainable Aquaculture. John Wiley & Sons, Ltd, pp. 373–388 (ISBN 978-0-470-27786-7.).
Misra, A.K., 2014. Climate change and challenges of water and food security. Int. J. Sustain. Built Environ. 3, 153–165. https://doi.org/10.1016/j.ijsbe.2014.04.006.
Monteleone, B., Borzí, I., Bonaccorso, B., Martina, M., 2022. Quantifying crop vulnerability to weather-related extreme events and climate change through vulnerability curves. Nat. Hazards. https://doi.org/10.1007/s11069-022-05791-0.

Moraes, B.S., Petersen, S.O., Zaiat, M., Sommer, S.G., Triolo, J.M., 2017. Reduction in greenhouse gas emissions from vinasse through anaerobic digestion. Appl. Energy 189, 21–30. https://doi.org/10.1016/j.apenergy.2016.12.009.
Moult, J.A., Allan, S.R., Hewitt, C.N., Berners-Lee, M., 2018. Greenhouse gas emissions of food waste disposal options for UK retailers. Food Policy 77, 50–58. https://doi.org/10.1016/j.foodpol.2018.04.003.
Mullon, C., Guillotreau, P., Galbraith, E.D., Fortilus, J., Chaboud, C., Bopp, L., Aumont, O., Kaplan, D., 2017. Exploring future scenarios for the global supply chain of tuna. Deep-Sea Research Part II: Topical Studies in Oceanography 140, 251–267. https://doi.org/10.1016/j.dsr2.2016.08.004.
Munn, Z., Pollock, D., Khalil, H., Alexander, L., Mclnerney, P., Godfrey, C.M., Peters, M., Tricco, A.C., 2022. What are scoping reviews? Providing a formal definition of scoping reviews as a type of evidence synthesis. JBI Evid Synth 20, 950–952. https://doi.org/10.11124/JBIES-21-00483.
Muringai, R.T., Mafongoya, P., Lottering, R.T., 2022. Sub-Saharan Africa freshwater fisheries under climate change: a review of impacts, adaptation, and mitigation measures. Fishes 7. https://doi.org/10.3390/fishes7030131.
Myers, S.S., Smith, M.R., Guth, S., Golden, C.D., Vaitla, B., Mueller, N.D., Dangour, A.D., Huybers, P., 2017. Climate change and global food systems: potential impacts on food security and undernutrition. Annu. Rev. Public Health 38, 259–277. https://doi.org/10.1146/annurev-publhealth-031816-044356.
Naga Raja Kumari, K., Narendra Nath, D., 2018. Ameliorative measures to counter heat stress in poultry. Worlds Poult. Sci. J. 74, 117–130. https://doi.org/10.1017/S0043933917001003.
Nawaz, A.H., Amoah, K., Leng, Q.Y., Zheng, J.H., Zhang, W.L., Zhang, L., 2021. Poultry response to heat stress: its physiological, metabolic, and genetic implications on meat production and quality including strategies to improve broiler production in a warming world. Frontiers in Veterinary Science 8.
Nelitz, M., Boardley, S., Smith, R., 2013. Tools for Climate. Change Vulnerability Assessment for Watersheds.
Nelson, G.C., Rosegrant, M.W., Koo, J., Robertson, R.D., Sulser, T., Zhu, T., Ringler, C., Msangi, S., Palazzo, A., Batka, M., et al., 2023. Climate Change: Impact on Agriculture and Costs of Adaptation. Available online. https://ebrary.ifpri.org/digital/collection/p15738coll2/id/130648. accessed on 22 February.
Nelson, M.C., Ingram, S.E., Dugmore, A.J., Streeter, R., Peeples, M.A., McGovern, T.H., Hegmon, M., Arneborg, J., Kintigh, K.W., Brewington, S., et al., 2016. Climate challenges, vulnerabilities, and food security. Proc. Natl. Acad. Sci. 113, 298–303. https://doi.org/10.1073/pnas.1506494113.
Niu, C., Qi, Y., Guo, A., Chang, J., 2022. Grain yield and food security evaluation in the Yellow River Basin under climate change and water resources constraints. Frontiers in Water 4.
O'Brien, K.L., Leichenko, R.M., 2000. Double exposure: assessing the impacts of climate change within the context of economic globalization. Glob. Environ. Chang. 10, 221–232. https://doi.org/10.1016/S0959-3780(00)00021-2.
Odeku, K.O., 2013. Global climate change, threat to food safety and poverty. Mediterr. J. Soc. Sci. 4, 827–834. https://doi.org/10.5901/mjss.2013.v4n14p827.
Orengo Serra, K.L., Sanchez-Jauregui, M., 2021. Food supply chain resilience model for critical infrastructure collapses due to natural disasters. Br. Food J. 124, 14–34. https://doi.org/10.1108/BFJ-11-2020-1066.
Osei-Amponsah, R., Chauhan, S.S., Leury, B.J., Cheng, L., Cullen, B., Clarke, I.J., Dunshea, F.R., 2019. Genetic selection for thermotolerance in ruminants. Animals 9, 948. https://doi.org/10.3390/ani9110948.
Osman, A.I., Chen, L., Yang, M., Msigwa, G., Farghali, M., Fawzy, S., Rooney, D.W., Yap, P.-S., 2023. Cost, environmental impact, and resilience of renewable energy under a changing climate: a review. Environ. Chem. Lett. 21, 741–764. https://doi.org/10.1007/s10311-022-01532-8.
Oyas, H., Holmstrom, L., Kemunto, N.P., Muturi, M., Mwatondo, A., Osoro, E., Bitek, A., Bett, B., Githinji, J.W., Thumbi, S.M., et al., 2018. Enhanced surveillance for rift valley fever in livestock during El Niño rains and threat of RVF outbreak, Kenya, 2015–2016. PLoS Negl. Trop. Dis. 12, e0006353 https://doi.org/10.1371/journal.pntd.0006353.
Papathoma-Köhle, M., 2016. Vulnerability curves vs. vulnerability indicators: application of an Indicator-based methodology for debris-flow hazards. Nat. Hazards Earth Syst. Sci. 16, 1771–1790. https://doi.org/10.5194/nhess-16-1771-2016.
Papathoma-Köhle, M., Schlögl, M., Fuchs, S., 2019. Vulnerability indicators for natural hazards: an innovative selection and weighting approach. Sci. Rep. 9, 15026. https://doi.org/10.1038/s41598-019-50257-2.
Parajuli, R., Thoma, G., Matlock, M.D., 2019. Environmental sustainability of fruit and vegetable production supply chains in the face of climate change: a review. Sci. Total Environ. 650, 2863–2879. https://doi.org/10.1016/j.scitotenv.2018.10.019.
Parker, L., Bourgoin, C., Martinez-Valle, A., Läderach, P., 2019. Vulnerability of the agricultural sector to climate change: the development of a pan-tropical climate risk vulnerability assessment to inform sub-national decision making. PLoS One 14, e0213641. https://doi.org/10.1371/journal.pone.0213641.
Perdana, T., Onggo, B.S., Sadeli, A.H., Chaerani, D., Achmad, A.L.H., Hermiatin, F.R., Gong, Y., 2022. Food supply chain management in disaster events: a systematic literature review. International Journal of Disaster Risk Reduction 79. https://doi.org/10.1016/j.ijdrr.2022.103183.
Perez, M.L.; Sajise, A.J.U.; Arias, J.K.B.; Ramirez, J.B.; Purnomo, A.H.; Dipasupil, S.R.; Regoniel, P.A.; Nguyen, K.A.T.; Zamora, G.J.; Radjawane, I.M.; et al. n.d. Economic Analysis of Climate Change Adaptation Strategies in Selected Coastal Areas in Indonesia, Philippines and Vietnam.
Phelan, A. (Anya), Meissner, K., Humphrey, J., Ross, H., 2022. Plastic pollution and packaging: corporate commitments and actions from the food and beverage sector. J. Clean. Prod. 331, 129827 https://doi.org/10.1016/j.jclepro.2021.129827.
Pollock, D., Davies, E.L., Peters, M.D.J., Tricco, A.C., Alexander, L., McInerney, P., Godfrey, C.M., Khalil, H., Munn, Z., 2021. Undertaking a scoping review: a practical guide for nursing and midwifery students, clinicians, researchers, and academics. J. Adv. Nurs. 77, 2102–2113. https://doi.org/10.1111/jan.14743.
Poulain, F., Himes-Cornell, A., Shelton, C., 2018. Methods and tools for climate change adaptation in fisheries and aquaculture. In: Impacts of Climate Change on Fisheries and Aquaculture, 627. FAO Fisheries and Aquaculture Technical Paper. ISBN 978-92-5-130607-9.
Powell, N., Ji, X., Ravash, R., Edlington, J., Dolferus, R., 2012. Yield stability for cereals in a changing climate. Funct. Plant Biol. 39, 539–552. https://doi.org/10.1071/FP12078.
Proag, V., 2014. The concept of vulnerability and resilience. Procedia Economics and Finance 18, 369–376. https://doi.org/10.1016/S2212-5671(14)00952-6.
Puma, M.J., Bose, S., Chon, S.Y., Cook, B.I., 2015. Assessing the evolving fragility of the global food system. Environ. Res. Lett. 10 https://doi.org/10.1088/1748-9326/10/2/024007.
Pyykkö, H., Suoheimo, M., Walter, S., 2021. Approaching sustainability transition in supply chains as a wicked problem: systematic literature review in light of the evolved double diamond design process model. Processes 9, 2135. https://doi.org/10.3390/pr9122135.
Ragagnin, M.N., McCarthy, I.D., Fernandez, W.S., Tschiptschin, A.P., Turra, A., 2018. Vulnerability of juvenile hermit crabs to reduced seawater pH and shading. Mar. Environ. Res. 130–140. https://doi.org/10.1016/j.marenvres.2018.10.001.
Rahman, M.M., Nguyen, R., Lu, L., 2022. Multi-level impacts of climate change and supply disruption events on a potato supply chain: an agent-based modeling approach. Agric. Syst. 201 https://doi.org/10.1016/j.agsy.2022.103469.
Raza, A., Razzaq, A., Mehmood, S.S., Zou, X., Zhang, X., Lv, Y., Xu, J., 2019. Impact of climate change on crops adaptation and strategies to tackle its outcome: a review. Plants (Basel) 8, 34. https://doi.org/10.3390/plants8020034.
Reddy, P.P., 2014. Climate Resilient Agriculture for Ensuring Food Security. Springer (ISBN 978-81-322-2199-9.).
Reid, G.K., Gurney-Smith, H., Flaherty, M., Garber, A., Forster, I., Brewer-Dalton, K., Knowler, D., Marcogliese, D., Chopin, T., Moccia, R., et al., 2019. Climate change and aquaculture: considering adaptation potential. Aquac. Environ. Interact. 11, 603–624. https://doi.org/10.3354/aei00333.
Rice, J.B., Caniato, F., 2003. Building a Secure and Resilient Supply Network. Supply Chain Management Review, 7, pp. 22–30. NO. 5 (SEPT./OCT. 2003). ILL.
Riesenegger, L., Hübner, A., 2022. Reducing food waste at retail stores—an explorative study. Sustainability 14, 2494. https://doi.org/10.3390/su14052494.
Robinson, J.P.W., Maire, E., Bodin, N., Hempson, T.N., Graham, N.A.J., Wilson, S.K., MacNeil, M.A., Hicks, C.C., 2022. Climate-induced increases in micronutrient availability for coral reef fisheries. One Earth 5, 98–108. https://doi.org/10.1016/j.oneear.2021.12.005.
Rodríguez-Cruz, L.A., Moore, M., Niles, M.T., 2021. Puerto Rican farmers' obstacles toward recovery and adaptation strategies after hurricane Maria: a mixed-methods approach to understanding adaptive capacity. Frontiers in Sustainable Food Systems 5. https://doi.org/10.3389/fsufs.2021.662918.
Rodríguez-Cruz, L.A., Álvarez-Berríos, N., Niles, M.T., 2022. Social-ecological interactions in a disaster context: Puerto Rican farmer households' food security after hurricane Maria. Environ. Res. Lett. 17 https://doi.org/10.1088/1748-9326/ac6004.
Rojas-Downing, M.M., Nejadhashemi, A.P., Harrigan, T., Woznicki, S.A., 2017. Climate change and livestock: impacts, adaptation, and mitigation. Clim. Risk Manag. 16, 145–163. https://doi.org/10.1016/j.crm.2017.02.001.
Rolando, J.L., Turin, C., Ramírez, D.A., Mares, V., Monerris, J., Quiroz, R., 2017. Key ecosystem services and ecological intensification of agriculture in the tropical high-Andean Puna as affected by land-use and climate changes. Agric. Ecosyst. Environ. 236, 221–233. https://doi.org/10.1016/j.agee.2016.12.010.
Rosenzweig, C., Tubiello, F.N., 2007. Adaptation and mitigation strategies in agriculture: an analysis of potential synergies. Mitig Adapt Strat Glob Change 12, 855–873. https://doi.org/10.1007/s11027-007-9103-8.
Rother, B., Sosa, S., Kim, D., Kohler, L.P., Pierre, G., Kato, N., Debbich, M., Castrovillari, C., Sharifzoda, K., Heuvelen, E.V., et al., 2022. Tackling the global food crisis: impact, policy response, and the role of the IMF. IMF Notes 2022. https://doi.org/10.5089/9798400221972.002.A001.
Roukas, T., Kotzekidou, P., 2022. From food industry wastes to second generation bioethanol: a review. Rev. Environ. Sci. Biotechnol. 21, 299–329. https://doi.org/10.1007/s11157-021-09606-9.
Rousseau, J.-F., Xu, Y., 2021. The perfect storm: extreme weather events and speculation along cardamom commodity chains in Southwest China. Eurasian Geogr. Econ. 62, 178–201. https://doi.org/10.1080/15387216.2020.1792323.
Saeed, S., Makhdum, M.S.A., Anwar, S., Yaseen, M.R., 2023. Climate change vulnerability, adaptation, and feedback hypothesis: a comparison of lower-middle, upper-middle, and high-income countries. Sustainability 15, 4145. https://doi.org/10.3390/su15054145.
Sae-Lim, P., Kause, A., Mulder, H.A., Olesen, I., 2017. Breeding and genetics symposium: climate change and selective breeding in aquaculture1. J. Anim. Sci. 95, 1801–1812. https://doi.org/10.2527/jas.2016.1066.
Saiful Islam, A.H.Md., Barman, B.K., Murshed-e-Jahan, K., 2015. Adoption and impact of integrated rice–fish farming system in Bangladesh. Aquaculture 447, 76–85. https://doi.org/10.1016/j.aquaculture.2015.01.006.
Saravanakumar, V., Lohano, H.D., Balasubramanian, R., 2022. A district-level analysis for measuring the effects of climate change on production of rice: evidence from southern India. Theor. Appl. Climatol. 150, 941–953. https://doi.org/10.1007/s00704-022-04198-y.

Scheer, C., Rowlings, D.W., Migliorati, M.D.A., Lester, D.W., Bell, M.J., Grace, P.R., Scheer, C., Rowlings, D.W., Migliorati, M.D.A., Lester, D.W., et al., 2016. Effect of enhanced efficiency fertilisers on nitrous oxide emissions in a sub-tropical cereal cropping system. Soil Res. 54, 544–551. https://doi.org/10.1071/SR15332.
Schnitter, R., Berry, P., 2019. The climate change, food security and human health nexus in Canada: a framework to protect population health. Int. J. Environ. Res. Public Health 16. https://doi.org/10.3390/ijerph16142531.
Schollaert Uz, S., Ruane, A.C., Duncan, B.N., Tucker, C.J., Huffman, G.J., Mladenova, I. E., Osmanoglu, B., Holmes, T.R.H., McNally, A., Peters-Lidard, C., et al., 2019. Earth observations and integrative models in support of food and water security. Remote Sensing in Earth Systems Sciences 2, 18–38. https://doi.org/10.1007/s41976-019-0008-6.
Senapati, N., Stratonovitch, P., Paul, M.J., Semenov, M.A., 2019. Drought tolerance during reproductive development is important for increasing wheat yield potential under climate change in Europe. J. Exp. Bot. 70, 2549–2560. https://doi.org/10.1093/jxb/ery226.
Sharaan, M., Iskander, M., Udo, K., 2022. Coastal adaptation to sea level rise: an overview of Egypt's efforts. Ocean Coast. Manag. 218, 106024 https://doi.org/10.1016/j.ocecoaman.2021.106024.
Shitu, A., Liu, G., Muhammad, A.I., Zhang, Y., Tadda, M.A., Qi, W., Liu, D., Ye, Z., Zhu, S., 2022. Recent advances in application of moving bed bioreactors for wastewater treatment from recirculating aquaculture systems: a review. Aquaculture and Fisheries 7, 244–258. https://doi.org/10.1016/j.aaf.2021.04.006.
Singh, B.K., Delgado-Baquerizo, M., Egidi, E., Guirado, E., Leach, J.E., Liu, H., Trivedi, P., 2023. Climate change impacts on plant pathogens, food security and paths forward. Nat. Rev. Microbiol. 21, 640–656. https://doi.org/10.1038/s41579-023-00900-7.
Sistla, S.A., Roddy, A.B., Williams, N.E., Kramer, D.B., Stevens, K., Allison, S.D., 2016. Agroforestry practices promote biodiversity and natural resource diversity in Atlantic Nicaragua. PLoS One 11, e0162529. https://doi.org/10.1371/journal.pone.0162529.
Sofi, P.A., Ara, A., Gull, M., Rehman, K., Sofi, P.A., Ara, A., Gull, M., Rehman, K., 2019. Canopy Temperature Depression as an Effective Physiological Trait for Drought Screening. IntechOpen (ISBN 978-1-78984-781-9.).
Soni, A., Bremer, P., Brightwell, G., 2022. A comprehensive review of variability in the thermal resistance (D-values) of food-borne pathogens—a challenge for thermal validation trials. Foods 11, 4117. https://doi.org/10.3390/foods11244117.
Sossidou, E.N.; Tsiplakou, E.; Zervas, G. Options for Managing Livestock Production Systems to Adapt to Climate Change08n.
Sovacool, B.K., Bazilian, M., Griffiths, S., Kim, J., Foley, A., Rooney, D., 2021. Decarbonizing the food and beverages industry: a critical and systematic review of developments, sociotechnical systems and policy options. Renew. Sust. Energ. Rev. 143, 110856 https://doi.org/10.1016/j.rser.2021.110856.
Srinivasan, R., Giannikas, V., Kumar, M., Guyot, R., McFarlane, D., 2019. Modelling food sourcing decisions under climate change: a data-driven approach. Comput. Ind. Eng. 128, 911–919. https://doi.org/10.1016/j.cie.2018.10.048.
Stone, J., Rahimifard, S., 2018. Resilience in Agri-food supply chains: a critical analysis of the literature and synthesis of a novel framework. Supply Chain Manag. 23, 207–238. https://doi.org/10.1108/SCM-06-2017-0201.
Tagwi, A., 2022. The impacts of climate change, carbon dioxide emissions (CO2) and renewable energy consumption on agricultural economic growth in South Africa: ARDL approach. Sustainability (Switzerland) 14. https://doi.org/10.3390/su142416468.
Teixeira, E.I., de Ruiter, J., Ausseil, A.-G., Daigneault, A., Johnstone, P., Holmes, A., Tait, A., Ewert, F., 2018. Adapting crop rotations to climate change in regional impact modelling assessments. Sci. Total Environ. 616–617, 785–795. https://doi.org/10.1016/j.scitotenv.2017.10.247.
Tessema, B., Sommer, R., Piikki, K., Söderström, M., Namirembe, S., Notenbaert, A., Tamene, L., Nyawira, S., Paul, B., 2020. Potential for soil organic carbon sequestration in grasslands in East African countries: a review. Grassl. Sci. 66, 135–144. https://doi.org/10.1111/grs.12267.
Theusme, C., Avendaño-Reyes, L., Macías-Cruz, U., Correa-Calderón, A., García-Cueto, R. O., Mellado, M., Vargas-Villamil, L., Vicente-Pérez, A., 2021. Climate change vulnerability of confined livestock systems predicted using bioclimatic indexes in an arid region of México. Sci. Total Environ. 751, 141779 https://doi.org/10.1016/j.scitotenv.2020.141779.
Tong, S., Bambrick, H., Beggs, P.J., Chen, L., Hu, Y., Ma, W., Steffen, W., Tan, J., 2022. Current and future threats to human health in the Anthropocene. Environ. Int. 158, 106892 https://doi.org/10.1016/j.envint.2021.106892.
Tramblay, Y., Koutroulis, A., Samaniego, L., Vicente-Serrano, S.M., Volaire, F., Boone, A., Le Page, M., Llasat, M.C., Albergel, C., Burak, S., et al., 2020. Challenges for drought assessment in the Mediterranean region under future climate scenarios. Earth Sci. Rev. 210 https://doi.org/10.1016/j.earscirev.2020.103348.
Tran, N., Chan, C.Y., Aung, Y.M., Bailey, C., Akester, M., Cao, Q.L., Trinh, T.Q., Hoang, C. V., Sulser, T.B., Wiebe, K., 2022. Foresighting future climate change impacts on fisheries and aquaculture in Vietnam. Frontiers in Sustainable Food Systems 6. https://doi.org/10.3389/fsufs.2022.829157.
Tubiello, F.N., Karl, K., Flammini, A., Gütschow, J., Obli-Laryea, G., Conchedda, G., Pan, X., Qi, S.Y., Halldórudóttir Heiðarsdóttir, H., Wanner, N., et al., 2022. Pre- and post-production processes increasingly dominate greenhouse gas emissions from agri-food systems. Earth System Science Data 14, 1795–1809. https://doi.org/10.5194/essd-14-1795-2022.
Tyler, N.J.C., Hanssen-Bauer, I., Førland, E.J., Nellemann, C., 2021. The shrinking Resource Base of pastoralism: Saami reindeer husbandry in a climate of change. Frontiers in Sustainable Food Systems 4. https://doi.org/10.3389/fsufs.2020.585685.
Umar, M., Wilson, M., Heyl, J., 2017. Food network resilience against natural disasters: a conceptual framework. SAGE Open 7. https://doi.org/10.1177/2158244017717570.
UNFCCC, 2007. Climate Change: Impacts, Vulnerabilities and Adaptation in Developing Countries.
Valta, K., Moustakas, K., Sotiropoulos, A., Malamis, D., Haralambous, K.J., 2016. Adaptation measures for the food and beverage industry to the impact of climate change on water availability. Desalin. Water Treat. 57, 2336–2343. https://doi.org/10.1080/19443994.2015.1049407.
Vermeulen, S.J., Campbell, B.M., Ingram, J.S.I., 2012. Climate change and food systems. Annu. Rev. Environ. Resour. 37, 195–222. https://doi.org/10.1146/annurev-environ-020411-130608.
Vicente-Serrano, S.M., Beguería, S., Gimeno, L., Eklundh, L., Giuliani, G., Weston, D., El Kenawy, A., López-Moreno, J.I., Nieto, R., Ayenew, T., et al., 2012. Challenges for drought mitigation in Africa: the potential use of geospatial data and drought information systems. Appl. Geogr. 34, 471–486. https://doi.org/10.1016/j.apgeog.2012.02.001.
Vicente-Vicente, J.L., Doernberg, A., Zasada, I., Ludlow, D., Staszek, D., Bushell, J., Hainoun, A., Loibl, W., Piorr, A., 2021. Exploring alternative pathways toward more sustainable regional food systems by foodshed assessment – city region examples from Vienna and Bristol. Environ. Sci. Pol. 124, 401–412. https://doi.org/10.1016/j.envsci.2021.07.013.
de Vries, M., Yigrem, S., Vellinga, T., 2016. Greening of Ethiopian Dairy Value Chains: Evaluation of Environmental Impacts and Identification of Interventions for Sustainable Intensification of Dairy Value Chains.
Wang, D., Jenkins, K., Forstenhäusler, N., Lei, T., Price, J., Warren, R., Jenkins, R., Guan, D., 2021. Economic impacts of climate-induced crop yield changes: evidence from agri-food industries in six countries. Clim. Chang. 166 https://doi.org/10.1007/s10584-021-03062-8.
Wang, Z., He, F., Fang, W., Liao, Y., 2013. Assessment of physical vulnerability to agricultural drought in China. Nat. Hazards 67, 645–657. https://doi.org/10.1007/s11069-013-0594-1.
Wang, Z., Jiang, J., Ma, Q., 2016. The drought risk of maize in the farming–pastoral ecotone in Northern China based on physical vulnerability assessment. Nat. Hazards Earth Syst. Sci. 16, 2697–2711. https://doi.org/10.5194/nhess-16-2697-2016.
Wasti, S., Sah, N., Mishra, B., 2020. Impact of heat stress on poultry health and performances, and potential mitigation strategies. Animals (Basel) 10, 1266. https://doi.org/10.3390/ani10081266.
Xie, W., Xiong, W., Pan, J., Ali, T., Cui, Q., Guan, D., Meng, J., Mueller, N.D., Lin, E., Davis, S.J., 2018. Decreases in global beer supply due to extreme drought and heat. Nature Plants 4, 964–973. https://doi.org/10.1038/s41477-018-0263-1.
Xie, W., Cui, Q., Ali, T., 2019. Role of market agents in mitigating the climate change effects on food economy. Nat. Hazards 99, 1215–1231. https://doi.org/10.1007/s11069-019-03646-9.
Xu, F., Li, Y., Ge, X., Yang, L., Li, Y., 2018. Anaerobic digestion of food waste – challenges and opportunities. Bioresour. Technol. 247, 1047–1058. https://doi.org/10.1016/j.biortech.2017.09.020.
Xu, R., Kiarie, E.G., Yiannikouris, A., Sun, L., Karrow, N.A., 2022. Nutritional impact of mycotoxins in food animal production and strategies for mitigation. J Animal Sci Biotechnol 13, 69. https://doi.org/10.1186/s40104-022-00714-2.
Yang, L., Ge, X., Wan, C., Yu, F., Li, Y., 2014. Progress and perspectives in converting biogas to transportation fuels. Renew. Sust. Energ. Rev. 40, 1133–1152. https://doi.org/10.1016/j.rser.2014.08.008.
Yang, Y., Xu, X., 2015. Post-disaster grain supply chain resilience with government aid. Transportation Research Part E: Logistics and Transportation Review 76, 139–159. https://doi.org/10.1016/j.tre.2015.02.007.
Yeni, F., Alpas, H., 2017. Vulnerability of global food production to extreme climatic events. Food Res. Int. 96, 27–39. https://doi.org/10.1016/j.foodres.2017.03.020.
Yue, Y., Wang, L., Li, J., Zhu, A., 2018. An EPIC model-based wheat drought risk assessment using new climate scenarios in China. Clim. Chang. 147, 539–553. https://doi.org/10.1007/s10584-018-2150-1.
Zajdband, A.D., 2011. Integrated agri-aquaculture systems. In: Lichtfouse, E. (Ed.), Genetics, Biofuels and Local Farming Systems. Springer Netherlands, Dordrecht, pp. 87–127. Sustainable Agriculture Reviews. ISBN 978-94-007-1521-9.
Zeuli, K., Nijhuis, A., Macfarlane, R., Ridsdale, T., 2018. The impact of climate change on the food system in Toronto. Int. J. Environ. Res. Public Health 15. https://doi.org/10.3390/ijerph15112344.
Zsögön, A., Peres, L.E.P., Xiao, Y., Yan, J., Fernie, A.R., 2022. Enhancing crop diversity for food security in the face of climate uncertainty. Plant J. 109, 402–414. https://doi.org/10.1111/tpj.15626.
Zurek, M., Hebinck, A., Selomane, O., 2021. Looking across diverse food system futures: implications for climate change and the environment. Q Open 1, 1–39. https://doi.org/10.1093/qopen/qoaa001.