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D 2.1 - Identification of Gaps and Food Security Drivers

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About SecureFood

The European Union's (EU) Farm to Fork strategy, the Biodiversity strategy, and the European Green Deal lay down necessary actions that set a long-term vision for how to change how we produce, distribute, and consume food.

In response to these ambitious aims, SecureFood adopts an integrated systems-thinking approach that acknowledges and embraces the complexity of the food supply chain, including all the actors, elements, processes, activities, infrastructure, and essential services of importance in the production, distribution, and consumption of food to maximize the food supply chain resilience.

SecureFood aims to create an ecosystem of scientific knowledge, collaborative processes, and digital tools that will provide evidence-based indications of the risks and vulnerabilities of the different food value categories in other geographies to safeguard food security and ensure that a secure and resilient food supply chain is assured.

The two crucial pillars of the program are the Food Systems Resilience Management Framework with connected resilience and sustainability orientations, as well as a Resilience Governance Framework that draws upon all of the collaborative principles and guidelines of the successful cooperation between the food supply chain stakeholders, which will be created, tested and demonstrated in real life case studies. These two frameworks will function as applicability and sustainability mechanisms for organizing and adopting the project's results by applying the developed scientific knowledge and enhancing the food system's resilience at different levels.

The ambition of the program consists of four critical dimensions, which are: 1) the evolution of scientific knowledge and development of the exploratory approach, combining research approach methods that facilitate the risk identification process; 2) the successful safeguarding of the food supply by framing the system resilience and broadening its lens, as well as by assessing and measuring it through a holistic approach which goes beyond national borders and strategies; 3) the acceleration of the transformation of the food systems network, which can be achieved by applying a systematic agency driven collaborative governance approach; 4) and finally, the application of innovative scientific knowledge with the use of advanced digital tools, which will contribute to the successful collection and processing of data sets from several platforms to reshape and redesign the food system trajectory.

The methodology employed in this program is based on three foundational and interconnected pillars: the scientific knowledge (existing and developing), the collaborative principles which are dynamically integrated into the methodology, and the development of digital solutions that will cover all parts of the project (forecasting, statistical analysis, etc.)

PROJECT PARTNERS

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List of Abbreviations and Acronyms

Acronym	Meaning
ADFSC	Abu Dhabi Food Security Centre
AI	Artificial Intelligence
AFD	French Development Agency
AgMIP	Agricultural Model Intercomparison and Improvement Project
AMIS	Agricultural Market Information Systems
ANC	Areas facing Natural Constraints
CAC	Codex Alimentarius Commission
CAP	Common Agricultural Policy
CEN	European Committee for Standardization
CENELEC	European Committee for Electrotechnical Standardization
CFS	Committee on world Food Security
CFP	Common Fisheries Policy
CIDA	Canadian International Development Agency
CoC	Code of Conduct
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CSIS	Centre for Strategic & International Studies
CSP(s)	Common Strategic Plan(s)
COM	Communication
DDG	Deputy Director General
DEFRA	Department for Environment, Food & Rural Affairs, UK
DLT	Distributed Ledger Technology
DT	Digital Twin
EC	European Commission
EFM	European Farmers Movement
EFSA	European Food Safety Authority
EFSCM	European Food Security Crisis preparedness and response Mechanism
ELMs	Environmental Land Management schemes
ERA	European Research Area
ESRC	Economic and Social Research Council
ETP	European Technology Platform
EU	European Union
FAO	Food and Agricultural Organization
FFEM	French Facility for Global Environment
FLW	Food Loss and Waste
FSDS	Federal Sustainable Development Strategy
FSMS	Food Safety Management System
FTA	Free Trade Agreements
GAFTA	Global Agribusiness Trade Association

Acronym	Meaning
GFSI	Global Food Security Index
GPC	Global Pulse Confederation
GST	Goods and Services Tax
HACCP	Hazard Analysis Critical Control Point
HLEG	High-Level Expert Group
IoT	Internet of Things
ISO	International Organisation for Standardisation
IUU	Illegal, unreported, and unregulated
MEAE	French Ministry for Europe and Foreign Affairs
MPG	Minimum Price Guarantee
NESA	Finnish National Emergency Supply Agency
NESO	National Emergency Supply Organisation
NGO	Non-Governmental Organisation
ODA	Official Development Assistance
OECD	Organization for Economic Co-operation Development
PACE	Platform for Accelerating the Circular Economy
PDCA	Plan Do Check Act
QMS	Quality Management System
RAI	Responsible Agricultural Investment initiative
RAS	Recirculating Aquaculture Systems
R&I	Research & Innovation
SCCP	Scottish Climate Change Adaptation Programme
SDG	Sustainable Development Goals
SFSCs	Short Food Supply Chains
SSFS	European Partnership on Safe and Sustainable Food Systems
TC	Technical Committee
TFEU	Treaty on the Functioning of the European Union
TPDS	Targeted Public Distribution System
UAE	United Arab Emirates
UN	United Nations
UNGC	United Nations Global Compact
USDA	United States Department of Agriculture
USNIC	United States National Intelligence Council
WP	Work Package
WFP	World Food Programme
WHO	World Health Organization
WTO	World Trade Organisation

Executive Summary

The SecureFood project's WP2 (Background analysis, food security drivers, requirements, and high-level reference architecture) is essential for identifying food security factors, assessing vulnerabilities, and developing a resilient food system framework. WP2 includes four critical tasks: Task 2.1 involves a literature and regulatory review in mapping food security across the EU, highlighting gaps and weaknesses, while Task 2.2 analyses the drivers of food security by looking at each of its pillars, like availability, access, and sustainability. Task 2.3 converts findings into practical requirements by engaging stakeholders to align SecureFood's solutions with sector-specific needs. Finally, Task 2.4 consolidates these insights into a reference architecture that supports scenario-building and case study development in WP3 and WP6. D2.1 documents WP2's findings, specifically focusing on connecting theoretical analysis with practical applications for future tasks. Designed for all SecureFood partners, policymakers, researchers, and technical teams, D2.1 establishes a foundation for informed decision-making across the project. By mapping food security challenges and resilience mechanisms, this deliverable supports other work packages, notably WP3's Task 3.1, where resilience drivers contribute to foresight analysis and scenario development, and WP6, where these identified drivers shape criteria for testing, co-creating, scaling up, and evaluating project innovations.

The methodological approach for D2.1 combines a multi-layered background analysis with an extensive literature review, empirical data collection, and a sectoral case study analysis. The background analysis conducted in Task 2.1 provides a structured view of current food security dynamics. It explores trends like climate change, urbanization, and shifting consumer behaviours, which present unique challenges to food production, distribution, access, and consumption across Europe. This analysis further reviews EU and international frameworks and guidelines from sources such as the EC, FAO, and WTO, situating SecureFood within an established regulatory and policy context and identifying gaps in these frameworks where new resilience strategies could be beneficial. Global initiatives, such as the UN's SDGs and the World Food Programme Framework for Resilience, are explored alongside EU policies such as the Farm to Fork Strategy, Biodiversity Strategy, and European Green Deal. These policies emphasize sustainable practices, responsible resource management, and resilience in food systems to address increasing global pressures on food security.

Moreover, the document examines national and regional practices, such as Scotland's Good Food Nation Plan and Norway's food security framework, which provide practical insights into localized resilience-building efforts. An assessment of the standardization landscape, from the ISO 22000 family of standards to CEN initiatives, highlights ongoing efforts to ensure food safety, manage resources sustainably, and support interoperable systems in the food sector. Together, these layers constitute a baseline for mapping food security drivers and developing interventions tailored to the EU's diverse food systems, supporting SecureFood's alignment with European and international resilience efforts.

The conceptual framework in D2.1 structures the food security drivers into six pillars (availability, access, utilization, stability, agency, and sustainability), each influencing the EU food systems differently on a short- and long-term basis. These six pillars serve as a conceptual foundation for SecureFood's resilience frameworks, offering a comprehensive understanding of the interconnected factors impacting food security across the EU. Within these six pillars, SecureFood examines and categorizes various drivers, including internal and external factors to the food value chain and affecting food security. The analysis covers drivers across five key categories: Biophysical and Environmental, Technological, Innovation and Supply Chain, Market and Economic, Political and Institutional, and Socio-Cultural and Demographic. The

biophysical and environmental drivers assess the impact of climate variability, natural resource constraints, and natural disasters, which primarily affect food production and crop yield stability. For instance, frequent droughts or flooding events compromise soil health and reduce yields, necessitating adaptive practices to maintain food availability and increase crop resilience. Technological and Innovation drivers explore how advancements like the Internet of Things, Blockchain, and Artificial Intelligence can enhance traceability, efficiency, and transparency across the supply chain while highlighting the challenges of digital tool adoption in less technologically advanced sectors. In addition, this category highlights the role of research and business innovation in responding to the challenges threatening food system resilience. Market and Economic drivers include price volatility, trade dependencies, and labour shortages that mainly affect food affordability and accessibility, especially for economically vulnerable populations. Political and Institutional drivers focus on policy decisions, regulatory compliance, and governance frameworks, evaluating how existing policies can support or hinder food security goals. This category further investigates the destabilization factors of national and international political instabilities. Socio-Cultural and Demographic drivers consider population trends, urbanization, and shifting consumer behaviours, which alter food demand and preferences. The interlinks and trade-offs between these drivers are also addressed, identifying key synergies and areas of conflict that could influence intervention strategies. For instance, technological innovation may boost supply chain transparency but exacerbate economic disparities if access to digital tools is limited to specific sectors or regions. Similarly, biophysical factors such as soil health and climate resilience interconnect with political drivers, requiring policy-level support to implement sustainable agricultural practices across the EU. Mapping these drivers with specific intervention targets provides actionable insights into where policy adjustments, technological support, economic incentives, management strategies, or financial investments could enhance resilience across each pillar, establishing a foundation for developing targeted scenarios in WP3.

Validation of these drivers and in-depth analysis of sectoral challenges are further explored through SecureFood's case studies and stakeholder feedback obtained via two questionnaires (the EU Survey and the Ad Hoc Questionnaire). The first targeted a broad audience across the food supply chain to gauge perceptions of food security risks and priorities. Questions covered demographic details and grouped hazards across categories like biophysical hazards, supply chain disruptions, and market volatility. Respondents provided insights into how these risks impact current operations and their anticipated effects on future food security, highlighting region-specific and sectoral differences in resilience needs. For example, respondents from coastal regions raised specific concerns about fisheries and aquaculture sustainability, while those in landlocked areas prioritized crop resilience and water scarcity. This feedback is instrumental in refining SecureFood's understanding of varied resilience needs across Europe's diverse food landscape. In addition, the Ad Hoc Questionnaire engaged case study participants from the four targeted food sectors of SecureFood (grains, milk and dairy, fruits and vegetables, and fish and aquaculture) to gather sector-specific insights into resilience drivers and vulnerabilities. Using a 3-point Likert scale, this questionnaire assessed the likelihood, vulnerability, and impact of various hazards within each sector, providing data to calculate a Mean Risk Exposure and Risk Index for each hazard. These indices highlight priority areas for intervention, such as soil health for grains, climate resilience for aquaculture, and market stability for dairy.

Furthermore, qualitative feedback from case study participants deepened insights into unique sectoral challenges, capturing nuances in food actors' needs that might not emerge from quantitative data alone. Follow-up consultations with end-users provided opportunities for clarification and additional input, ensuring that SecureFood's findings present a comprehensive perspective on sectoral vulnerabilities and resilience capacities. These combined insights support WP3's scenario development and provide a realistic foundation for WP6's case studies testing, aligning SecureFood's frameworks with the practical needs of EU food systems.

The outcomes of D2.1 feed directly into subsequent tasks and work packages within the SecureFood project, creating a solid base for future deliverables and implementation phases. This deliverable's insights and empirical data will inform the development of WP3's scenario-building exercises, designed to model potential disruptions and resilience strategies based on the identified food security drivers. Moreover, D2.1's findings will guide WP6's testing and co-creation phase, where the validated drivers will be integrated into the four case studies to strengthen the innovation testing plans. By linking the conceptual framework, empirical findings, and targeted interventions, this document equips SecureFood with the necessary foundation to advance toward building a resilient, sustainable, and adaptive food system for the EU, capable of withstanding and recovering from diverse, evolving challenges.

1 Introduction

1.1 WP2 Objectives and Tasks

Food security remains a cornerstone of human livelihood, well-being, and economic stability that must be preserved in a world of increasing complexity and interdependence. The SecureFood project responds to urgent and multi-dimensional challenges impacting food systems, from climate change and resource constraints to political instability and economic fluctuations. These factors present significant risks to food systems, requiring a robust, coordinated response that can ensure food security across diverse supply chains. SecureFood's core aim is to develop an ecosystem to identify, respond to, and mitigate the risks and vulnerabilities inherent in diverse food supply chains.

As the backbone of the SecureFood project, WP2 delivers critical insights that underpin resilience, sustainability, and adaptability within food systems. This work package consolidates essential knowledge on food security and provides insights that form the backbone for designing and developing SecureFood solutions, including its models, frameworks, and tools. WP2 undertakes an in-depth analysis of food security vulnerabilities, identifies its main drivers, and defines user requirements and reference architecture to support the project’s ecosystem. These efforts are structured around four main tasks, each contributing to a robust foundation for the project’s strategic goals:

- T2.1. Background analysis, state of play, and identification of gaps: It undertakes a comprehensive literature review and regulatory analysis to map the current food security landscape in the EU, identifying vulnerabilities and areas for improvement. This task includes gathering perspectives from diverse stakeholders through surveys, helping to clarify specific needs and challenges across the food supply chain, which will inform the work of WP6.
- T2.2. Food security drivers and targeted interventions: Building on the findings from T2.1, this task examines the primary drivers influencing food security by looking at the extended food security pillars (see section 4.1). The analysis integrates end-user insights with literature-based findings, creating a framework to understand both immediate and long-term factors that impact food security, thus contributing directly to WP3 by supporting the development of scenarios for food system resilience.
- T2.3. User requirements, use cases, and KPIs definition: This task engages end-users across the food supply chain to gather and refine a detailed set of requirements, capturing user expectations, capabilities, and needs within the SecureFood ecosystem. These requirements ensure that the developed models, frameworks, and digital tools are user-centered and effective in addressing real-world challenges, laying the groundwork for the system requirements and WP6 activities. Use cases outline specific tasks that users can accomplish with SecureFood solutions, while KPIs determine what will be tested, measured, and validated during the case studies.
- T2.4. System requirements and high-level reference architecture: It synthesizes insights from previous tasks to design a reference architecture that supports SecureFood’s digital, collaborative, and governance solutions. This architecture will guide subsequent project phases, particularly tool development, scenario planning, and policy recommendations, ensuring that each component aligns with the overall goals of building a resilient, adaptive food system.

1.2 Purpose of the Document

Deliverable 2.1, "Identification of Gaps and Food Security Drivers," consolidates the findings from T2.1 and T2.2, offering a strategic assessment of food security vulnerabilities and resilience drivers within the EU. As a foundational document, D2.1 supports SecureFood's future critical tasks and work packages, particularly T2.3, WP3 (Food systems' vulnerabilities and interdependencies – Risk and resilience governance and management), and WP6 (Co-creation, testing, scaling-up and evaluation of project's innovations), which entail the definition of user requirements, creating scenarios, and developing case studies. Through synthesizing literature and stakeholder engagement, D2.1 offers a roadmap to address critical food security gaps and highlights resilience drivers that can reinforce supply chain adaptability.

The scope of D2.1 extends beyond reporting findings. It provides actionable insights to aid decision-making and strategic planning across SecureFood. By bridging WP2's theoretical framework with the practical needs of later work packages, D2.1 will guide the scenario development and foresight analysis in WP3 and influence resilience assessment and policy recommendations in WP7 (Culture-building activities, policy recommendations, and best practices). As a comprehensive resource, D2.1 underpins SecureFood's goal of creating a food system that is both crisis-resilient and adaptable to evolving challenges, making it a vital tool for project stakeholders and partners.

1.3 Intended Readership and Connection to Other Deliverables

This deliverable is a stand-alone resource for all SecureFood project partners and will be instrumental in guiding the upcoming work packages. It is designed for a broad readership, including project partners, consortium members, policymakers, researchers, and technical teams engaged in shaping, implementing, and participating in food systems resilience-building activities. This deliverable offers critical insights into the landscape of food security by identifying resilience drivers and areas of vulnerability, thus enabling informed decision-making across the project.

D2.1 is pivotal in supporting T2.3 and other work packages by consolidating a framework of food security challenges and resilience mechanisms. It aids Task 2.3 in defining user requirements and capturing end-user needs and expectations for the SecureFood ecosystem. Additionally, D2.1 is essential to WP3's Task 3.1, where the identified drivers underpin the foresight analysis and scenario development. These scenarios will assess food systems' strengths and vulnerabilities, supporting the development of robust digital tools by ensuring they address practical food security challenges. D2.1's findings also feed into Task 3.2, which will help evaluate the system's adaptability to potential disruptions and support the implementation of targeted interventions to increase food system resilience, anchoring WP3 in a grounded understanding of food security dynamics. By highlighting key drivers and interventions, D2.1 equips WP3 with realistic insights into food security needs, reducing the risk of functional errors in digital solutions development.

Moreover, D2.1 is a foundation for WP6, "Co-creation, Testing, Scaling-up, and Evaluation of Project Innovations," informing T6.1 by defining evaluation criteria and KPIs for case studies. For SecureFood's case studies on different food categories (grains, fruits and vegetables, milk and dairy products, and fish and aquaculture products), D2.1 provides a basis for realistic scenario development by outlining the interrelations, impacts, and significance of food security drivers from T2.1 and T2.2. In doing so, D2.1 ensures that case studies are effectively aligned with real-world food security needs, making it a central resource in SecureFood's goal of fostering resilient, sustainable food systems.

2 General Methodological Approach

The methodological approach of this study integrates multiple layers of analysis to provide a comprehensive understanding of food security in the EU. The approach begins with an extensive background analysis examining the future dynamics of food security within the EU and internationally, aiming to anticipate emerging issues affecting food systems' resilience. This analysis explores complex trends such as climate change, urbanization, and demographic shifts, each of which poses unique challenges to food production, distribution, and access. The background analysis includes an extensive literature review of EU and global regulatory frameworks, standards, and guidelines to ground these insights within a regulatory and policy context. Key sources include European Commission directives, FAO and WTO guidelines, and national food security plans, providing a view of how current policies support or limit food security and where improvements could enhance resilience.

Additionally, we examined the activities and outcomes of major national and international initiatives, including the EU's Farm to Fork Strategy and the UN SDGs. This contextual grounding enables SecureFood to identify opportunities for alignment and potential synergies with ongoing global food security and sustainability efforts. A detailed review of past and current EU and other projects has been conducted to understand how much EU-funded projects cover the food sector and science.

The second phase of this methodology shifts focus to food security drivers, i.e., the factors that positively or negatively impact food availability, access, utilization, stability, agency, and sustainability. This section involves a thorough literature review to identify short- and long-term drivers that influence resilience across these six pillars of food security. Through a rigorous literature review, we categorized drivers such as climate variability, technological advancements, market dynamics, and socio-political factors. Understanding these drivers helps SecureFood to map vulnerabilities within the food system, ensuring that the interventions proposed are targeted and effective.

The third methodological component involves the validation of the literature findings regarding food security drivers and examining SecureFood's case studies, which aim to deliver in-depth insights into specific types and geographies of food systems. For this purpose, two questionnaires were developed and distributed to gather insights on food security risks and resilience strategies. The "EU Survey questionnaire," targeting a broad audience, began by collecting organizational demographics and then focused on hazards grouped by categories such as Biophysical and Environmental, Supply Chain, and Market and Economic. The survey gathered feedback on the perceived impacts of various hazards, their anticipated short- and long-term effects, and preferred resilience interventions. Responses provided valuable insights into regional and sectoral variations in food security challenges, helping to understand how these drivers affect different contexts.

Additionally, the questionnaire explored stakeholders' perspectives on resilience measures and prioritized food security pillars, enhancing the practical relevance of scenario development and digital tool design. These insights ensure project outputs align with real-world needs, contributing essential practical knowledge to SecureFood's goals. Both questionnaires are available in the Annexes for reference.

On the other hand, the "ad hoc questionnaire" targeted project beneficiaries and associated entities involved in SecureFood's case studies. These cases are centered on crucial food categories (grains, dairy, fruits and vegetables, and fish and aquaculture). They involve close, ongoing engagement with end-users to thoroughly capture their resilience needs, vulnerabilities, and response strategies. The ad hoc questionnaire prompted end-users to evaluate potential short- and long-term risks. It features a general section and a 3-point Likert scale to assess numerous hazards and threats concerning their likelihood, vulnerability, and impact on the food systems, thus offering a comprehensive view of sector-specific challenges. This allowed the calculation of "Mean Risk Exposure" and "Mean Risk Index," prioritizing risks for targeted interventions. An additional section assessed participants' views on SecureFood's solutions, helping align project deliverables with user expectations. This questionnaire collected crucial information on sector-specific factors like regulatory compliance, crisis preparedness, sustainability practices, and unique hazards, allowing end-users to evaluate potential short- and long-term risks and gain a comprehensive view of sector-specific challenges. In addition to questionnaire responses, further consultations with end-users were held to deepen insights into each sector's resilience needs and adaptive capacities. These follow-ups helped SecureFood clarify details, validate responses, and uncover new insights beyond the initial questionnaire. This approach allowed the team to capture sector-specific nuances, as different food categories face unique threats and have varied resilience capacities; for instance, climate variability impacts grain yields differently from the fish and aquaculture sector, where water quality is paramount. By addressing these distinctions, the case studies provide a holistic view of resilience across food supply chains, offering essential insights for WP6's testing and evaluation of project innovations.

Lastly, the analysis of responses from the survey and questionnaire provides detailed feedback that will guide later tasks and WPs within SecureFood. The information gathered from stakeholders and case study participants highlights critical areas for intervention, resilience gaps, and priority drivers that require attention. These findings are essential for informing scenario development in WP3 and testing project innovations in WP6. Together, these insights establish a foundational knowledge base that supports SecureFood's overarching goals of fostering secure, sustainable, and resilient food systems across Europe.

3 Background Analysis

3.1 Future Food Security Dynamics

The global food system faces profound challenges driven by population growth, climate change, and geopolitical crises while consumer preferences evolve rapidly. By 2050, the global population is expected to rise to nearly 10 billion, putting immense pressure on food production systems to meet increasing demands sustainably (Galanakis, 2024; United Nations, 2022). This growth, combined with urbanization, intensifies environmental pressures and the need for a resilient, efficient, and secure food supply (Tilman et al., 2011). The COVID-19 pandemic and ongoing geopolitical conflicts, such as the Russian-Ukrainian war, have further destabilized global food systems, underscoring the importance of adapting sustainable practices and optimized resource management (Galanakis et al., 2021; Galanakis, 2023).

In the EU, food supply chains are considered critical infrastructure, and the latest crises exposed the fragility of global food systems, highlighting the urgent need for resilient, flexible supply chains (Galanakis et al., 2023). Ensuring food security in this complex environment requires a holistic approach to agricultural productivity, environmental conservation, and the integration of advanced technologies (Foley et al., 2011). Research into optimizing supply chain designs and utilizing big data analytics is critical. Future food policies must focus on sustainability, environmental impact, and regulations that promote eco-friendly practices and reduce waste (Montanyà & Amat, 2023). Health-conscious policies should also reformulate food products to reduce unhealthy ingredients, encourage healthier diets, and increase transparency through labelling. Resilience in the agri-food sector can be enhanced through customer-centric decision-making, proximity-based distribution models, and cooperative frameworks, minimizing transportation distances and reducing spoilage and environmental impact (Perdana et al., 2022). Climate change exacerbates challenges, particularly for smallholder farmers in developing regions, where extreme weather events threaten food security and livelihoods (Gwambene et al., 2023). Key strategies include enhancing crop yields on underutilized lands, promoting sustainable farming practices, and encouraging dietary shifts toward plant-based alternatives, all while reducing food waste (Foley et al., 2011).

The food sector also needs to be transformed by improving efficiency, transparency, and traceability, as ensuring food safety and enabling greater traceability throughout the supply chain are critical to meet growing consumer demands for transparency (Rizou et al., 2020). Transformative policies are also needed at the governmental level, focusing on agroecological practices such as rooftop agriculture, vertical farming, precision agriculture, and shorter, more localized supply chains. At the same time, this transformation must align with the transition from fossil fuels to bio-based products and a climate-neutral economy and bioresource valorisation (Galanakis et al., 2021; Galanakis, 2022). The "blue bioeconomy," which leverages aquaculture and multitrophic systems, is also essential for future food sustainability (Galanakis et al., 2022). Innovations such as lab-grown meat are redefining how we consume food, contributing to reducing the environmental impact of traditional livestock farming. The latest needs to integrate with crop systems, adhering to the "One Health" principle, which promotes sustainability, public health, and environmental protection (WHO, 2017; Van Zanten et al., 2019).

Figure 1 illustrates an overview of the dynamic trajectory the food industry is embarking upon and the multifaceted dimensions that collectively constitute the future of food (Galanakis, 2024).

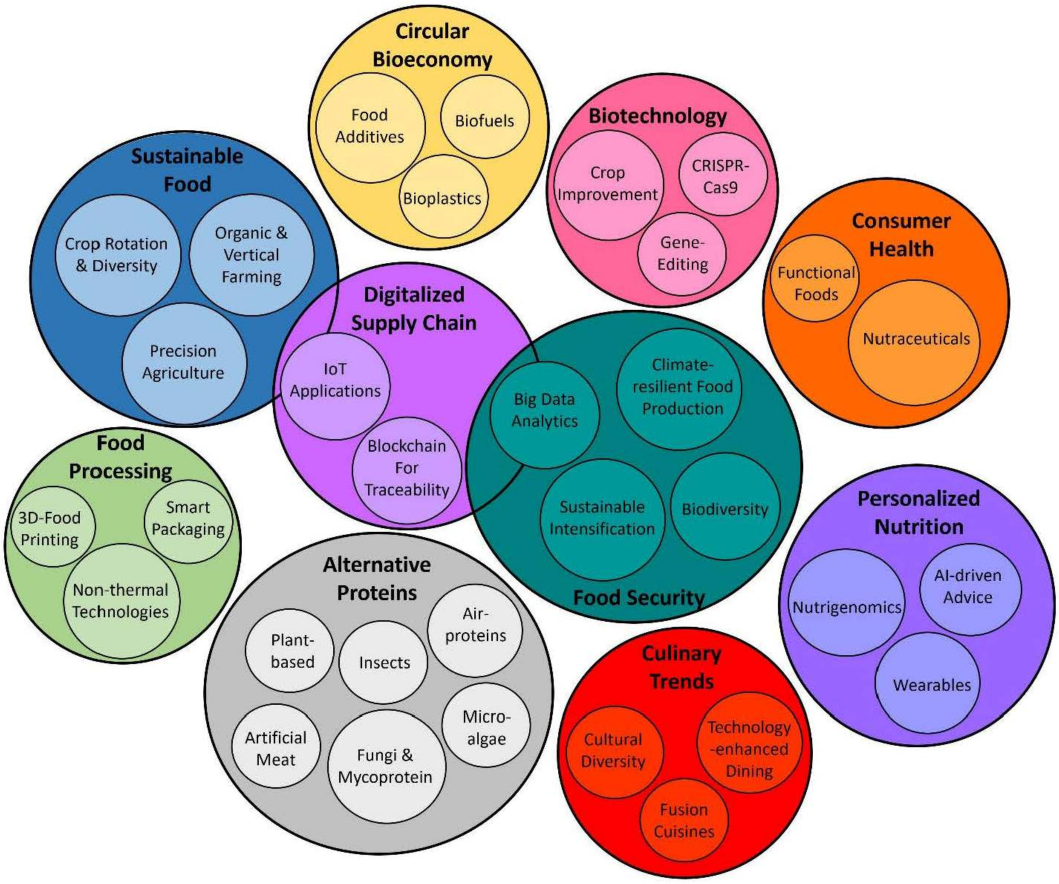

Figure 1 – An overview of the critical dimensions shaping the future of food[1].

Innovation and digitalization are crucial to tackling the global food system's challenges, and a shared commitment to a more resilient and sustainable supply chain is needed. Technologies like Artificial Intelligence (AI), the Internet of Things (IoT), and Distributed Ledger Technology (DLT) are transforming agriculture by enabling real-time monitoring, precision forecasting, and optimized management (Galanakis et al., 2023). These innovations reshape food production, management, and distribution, creating a more efficient and transparent system.

AI, primarily through machine learning, is pivotal in processing large datasets to enhance crop monitoring and management, replacing outdated methods and streamlining data analysis. This leads to more accurate forecasting, better decision-making, higher yields, and reduced resource inputs (Ahmadzadeh et al., 2023). IoT-enabled sensors complement this by providing real-time data across the food supply chain, enhancing efficiency from field operations to distribution (Rejeb et al., 2022).

Precision agriculture leverages soil sensors, satellite mapping, and automated tools to improve farming efficiency. These tools reduce the need for water, fertilizers, and pesticides, making agriculture more sustainable and profitable through optimized resource use (Abu et al., 2022).

[1] Adapted by Galanakis, 2024.

Despite their benefits, IoT solutions still face security, privacy, and complexity challenges, which must be addressed before broader adoption (Ahmadzadeh et al., 2023).

Digital Twins (DTs) are another promising technology that allows farmers to simulate farming scenarios, test strategies, and predict outcomes with high precision, improving crop yields and resource efficiency (Peladarinos et al., 2023). Combining DTs with AI and IoT further refines data-driven farming, enabling more sustainable food production systems.

Blockchain technology, known for its decentralized and tamper-resistant nature, improves transparency and trust in food supply chains by ensuring data integrity. It enables traceability from farm to fork, reducing fraud and identifying foodborne outbreaks (Singh & Sharma, 2023). Blockchain facilitates data sharing, shortens transaction times, and lowers operational costs (Ellahi et al., 2023). However, the widespread adoption of blockchain faces challenges, including the need for standardized procedures and stakeholder collaboration. Integration with IoT and other emerging technologies is also necessary (Galvez et al., 2018).

The ongoing digital transformation is reshaping the food retail sector, with e-commerce platforms and direct-to-consumer models overgrowing due to convenience and personalization. Sustainable and ethical retail practices emphasizing eco-friendly approaches are also rising (Rejeb et al., 2022). AI is crucial in analyzing large food databases, identifying flavour and food composition trends, and offering personalized recommendations (Tseng et al., 2023).

AI-driven tools are also used for sensory analysis and taste testing to improve food quality. Personalized marketing, guided by AI and big data analytics, is expected to grow, enabling companies to meet consumer demands more effectively (Ding et al., 2023). As online shopping expands, AI and big data are increasingly incorporated to enhance customer experiences, driving the food industry toward a more intelligent and sustainable future. Social media data, analysed through big data analytics, helps food companies align their products with consumer preferences (Masih & Joshi, 2021).

As we explore the evolving dynamics of food security, it becomes clear that successful interventions must be supported by comprehensive regulatory frameworks aligned with standardization processes, national plans, and best practices in different world regions. EU and national regulations play a pivotal role in shaping future food systems, ensuring sustainability, innovation, and resilience are embedded throughout the supply chain. These frameworks set food safety and production standards and promote adopting sustainable practices and harmonized solutions, facilitating international collaboration. Subsequently, examining the regulatory landscape, standardization processes, and best practices is crucial for enhancing food security and driving systemic improvements.

3.2 Global Initiatives and Emerging Practices

A part of the extensive literature review executed within this Deliverable included the essential findings and guidelines formulated by international and European organizations to build resilient food systems. These organizations are recognized globally for their expertise and provide comprehensive frameworks and recommendations to governments and stakeholders to ensure food security. Critical issues related to the food supply chain, including potential hazards and emerging drivers, are analysed globally and regionally. Insights from these leading organizations have informed the development of targeted recommendations and good practices. Given their importance and the recognized and well-grounded basis for their recommendations and frameworks, SecureFood shall consider the following representative references.

3.2.1 United Nations

The 2023 Global Sustainable Development Report emphasizes embracing transformations to accelerate progress towards the Sustainable Development Goals (SDGs) (Independent Group of Scientists appointed by the Secretary-General, 2023). Despite some advancements, challenges have multiplied since 2019, with crises such as the COVID-19 pandemic, climate change, and economic distress disrupting progress. The report advocates for a holistic approach to security, encompassing geopolitical, energy, climate, water, food, and social aspects. It underscores the importance of using time and resources judiciously, fostering solidarity, and driving systematic and strategic transformations. The report synthesizes knowledge on key transformations across various sectors and provides practical examples and tools for enhancing leadership and human capacities. It outlines the need for a systematic approach to understanding transformation processes and highlights the role of different levers in facilitating change. Additionally, the report emphasizes the evolution of the knowledge enterprise to better support transformation processes by generating knowledge from diverse sources and connecting it to decision-making. Through six chapters, the report assesses the current status, prospects, necessary actions, strategic frameworks, and the role of science in driving transformative action towards sustainable development.

3.2.2 World Food Programme (WFP)

The WFP has introduced a practical Framework and Orientation Note for building resilient food systems across the globe (WFP, 2022). This framework emphasizes the importance of addressing cross-cutting issues such as gender equality and women's empowerment, protection and accountability, nutrition integration, and environmental and social safeguards. The principles are aligned with contexts, considering local shocks, stressors, vulnerabilities, partnerships, capacities, and available funding. This framework outlines five key pathways to enhance food system resilience. Specifically, they include safeguarding food access and system functionality during and after crises through social protection; restoring natural resources and supporting climate-resilient local production; strengthening production and the overall value chains by linking them to food demand and building capacities among vulnerable groups; influencing food environments to promote nutritious and affordable options; supporting government policies and engaging stakeholders to create an enabling environment. These pathways can be customized and integrated at national, sub-national, and local levels to reinforce programming synergies for food resilience systems.

3.2.3 World Trade Organisation (WTO)

In alignment with its role in enhancing food security, the WTO has published a communication from the United States (WTO, 2023). This communication emphasizes that open global markets are crucial for transferring food from surplus to deficit regions, which helps stabilize markets by reducing the risk of food scarcity and mitigating price volatility. The global trade system facilitates diversified food sourcing, enabling companies throughout the supply chain to swiftly adapt to disruptions in specific food sources. Adopting new technologies and innovative approaches is vital to further enhancing global food security. This includes advancements in soil management, seeds, pest control, farm operations, and innovative managerial and operational strategies tailored to regional differences and contexts. A rulebased trading system governs Open markets, and these innovations have driven economic growth, providing vulnerable groups access to global markets. Governments play a crucial role in enhancing food security through sustainable agricultural production and accessible new technologies. Farmers and producers need policies that help them adapt to market disruptions and variable weather conditions and support their transition to more sustainable production practices. Governments should encourage sustainable agricultural practices while discouraging policies that lead to overproduction, resource misallocation, market distortions, or other negative environmental impacts.

3.2.4 Food and Agricultural Organization (FAO)

The FAO published the "Best Practices in Addressing the Major Drivers of Food Security and Nutrition to Transform Food Systems," focusing on valuable guidance in developing transformative and coherent policy portfolios (Carrasco et al., 2022). Report principles are aligned with climate resilience by enhancing crop production, food security, and nutrition. Enhancing economic resilience, diversifying diets, and reducing poverty and inequality are essential components supporting and reinforcing climate resilience efforts. Practices linked to specific transformative pathways, such as scaling up climate resilience, also generate significant impacts beyond food systems, highlighting the importance of coherence across sectors and systems. These practices are also designed to strengthen people's capacities and economic resilience, improve access to more nutritious food, and reduce poverty and inequalities. In regions facing the dual challenges of climate extremes and conflict, the FAO presents practices focused on building economic resilience, drawing on lessons from policy responses during the COVID-19 pandemic and efforts to bolster rural economies. Several case studies analyzing practical, real-world applications of strategies aimed at enhancing the resilience of food systems to withstand and recover from shocks demonstrate how the primary goal of climate resilience is effectively integrated with complementary objectives across additional transformative pathways. The case studies provide examples of policy instruments designed to transform food systems to enable them to become more resilient to the drivers behind rising levels of food insecurity and malnutrition and to improve people's access to affordable, healthy diets.

3.2.5 United Nations Global Compact (UNGC)

The United Nations Global Compact has developed the report titled "Scaling Up: Global Food Security and Sustainable Agriculture" to showcase the best-emerging practices and inspire a broader movement across all relevant sectors and industries toward a more food-secure and sustainable future (UN Global Compact, 2012). This report recommends several vital policies to enhance global food security and promote sustainable agriculture. Governments should significantly increase investment in agricultural development, including support for agricultural institutions, extension services, and infrastructure such as roads and storage facilities. Additionally, investments in rural development, particularly in sectors like education, healthcare, and clean water, are essential. To improve access to nutritious food, government policies should integrate nutrition into all industries and focus on ensuring year-round access to a diverse range of foods for everyone.

Furthermore, policies should support technological innovations that are accessible and applicable to small-scale and poor farmers and assist in scaling up successful pilot projects. Reducing trade barriers to cushion against localized price fluctuations, enhancing national safety net programs, creating emergency food reserves, and investing in risk management tools for producers are also critical steps. Finally, governments should promote corporate transparency and establish reporting guidelines for sustainable agriculture, encouraging businesses to prioritize food security and sustainable agricultural practices.

3.2.6 Global Agribusiness Trade Association (GAFTA) and Global Pulse Confederation (GPC)

The GPC and the GAFTA underscore the critical need for international cooperation to stabilize food security during crises, drawing on valuable insights from the COVID-19 pandemic (GPC & GAFTA, 2020). They have authored a report aimed at bolstering the global food supply chain through crucial actions focused on monitoring global stocks and projected usage of essential food commodities, exercising abundant caution concerning supply levels, evaluating logistics system performance to ensure timely food delivery, including enhancing the availability of containers for transporting both empty and loaded goods; and overseeing food production systems while facilitating the movement of labour and critical inputs essential for production at both the farm and processing levels. The report recommends that governments collaborate to develop a comprehensive strategy that stabilizes domestic production, facilitates food trade, and removes barriers restricting access to essential supplies. Governments should recognize global trade as a cornerstone of stable prices and food security. International trade support mitigates the impact of regional production shortfalls and supports critical revenue for farmers. It further recommends that government policies be based on a clear understanding of the interdependence between food-producing and food-deficit regions with any new measures considering the impact on existing contracts and goods already in transit to markets.

3.2.7 Committee on World Food Security (CFS)

The CFS provides a comprehensive reference document offering practical guidance on core recommendations for food security policies and actions (CSF, 2022). Key recommendations include establishing or strengthening inter-ministerial mechanisms for national strategies, with high-level coordination across ministries such as agriculture, health, education, and finance. The document advocates for creating multistakeholder platforms to design, implement, and monitor food policies, ensuring the inclusion of all affected groups. It also recommends mapping and tracking systems to coordinate actions, promote accountability among stakeholders, and consider the potential impacts of national food security strategies on other countries. The framework underscores the importance of strengthening the alignment and coherence of technical and financial contributions from international aid, regional banks, regional technical agencies, regional farmers' platforms, the private sector, and civil society organizations to effectively support regional and national strategies. It highlights the need for increased donor support to foster regional economic integration and coordinate regional policies on agricultural trade. Additionally, the GSF suggests considering strategic food reserves and strengthening regional value chains while simultaneously highlighting the importance of Official Development Assistance (ODA) in supporting public investment in social programs, infrastructure, and research.

3.2.8 OECD-FAO Collaboration

The Organisation for Economic Co-operation Development (OECD), in collaboration with the Food and Agricultural Organization (FAO) of the United Nations, published the "Food Security and Trade 2023" report to underscore the role of trade in food systems (OECD & FAO, 2023). Trade plays a vital role in ensuring food security, allowing countries to overcome limitations in land and water resources and meet their food needs beyond what domestic production could sustain. Policy measures should prioritize minimizing supply chain disruptions, diversifying sources, and introducing temporary relief measures. Countries facing internal conflicts and precarious food security situations are encouraged to focus on finding alternative supply sources and, in the short term, facilitating agricultural exports through logistical support. Maintaining trust in the international trading system as a reliable supply source is essential. Therefore, export restrictions should be avoided and, if implemented, should be lifted as quickly as possible. Trade can contribute to more sustainable agricultural production globally by promoting specialization in regions where crops can be grown efficiently without excessive land clearing or irrigation. Finally, the report emphasizes that food self-sufficiency is an expensive strategy for ensuring the availability of adequate and diverse foods. Policymakers should also continue to support the Agricultural Market Information Systems (AMIS) with stable funding and consider expanding its scope to include agricultural input markets, such as fertilizers, other commodities, and global food trade logistics.

3.2.9 European Food Security Crisis preparedness and response Mechanism (EFSCM)

The EFSCM has underscored the importance of systemic changes for sustainability, stressing that abrupt transitions can threaten food security. At an extraordinary meeting of the EFSCM, concerns about speculation in food markets were raised, with the Deputy Director General (DDG) emphasizing the transparency of EU institutions but acknowledging the difficulty of assessing the influence of large agricultural players on food supply chains (EFSCM, 2022). The European Farmers Movement (EFM) advocated for building wheat reserves in Member States to ensure food security in times of crisis. However, the European Commission noted the complexities of stock management and disposal. The rising reserves in China and India contribute to global market distortions, particularly affecting poorer nations. The EU's Common Agricultural Policy continues to prioritize food security, facing intensified challenges from climate change, geopolitical instability, and rising prices. The Commission focuses on immediate and long-term food security drivers, including environmental, economic, and societal factors (EFSCM, 2023a). The EFSCM also stressed the need for supply chain diversification, calling for policies that promote crop rotation, alternative crop production, and innovation. Coherent policy and trade diversification are vital, although over-reliance on a few partners could create vulnerabilities. A resilient Single Market, the promotion of short food supply chains, and sustainable consumption patterns are crucial to food security (EFSCM, 2023a). Effective crisis communication is essential, with EFSCM guidelines advocating for transparency, quick responses, media monitoring, and post-crisis evaluations to build trust and ensure informed responses (EFSCM, 2023b). Finally, a 2023 report on food security highlights ongoing risks like extreme weather, geopolitical tensions, and input cost volatility, stressing the need for coordinated, proactive action to safeguard food security and strengthen the EU's resilience (EFSCM, 2023c).

3.2.10 European Common Agricultural Policy (CAP)

The Directorate-General for Agriculture and Rural Development of the European Commission has developed the "Mapping and Analysis of CAP Strategic Plan" to assess the joint efforts for 2023-2027 (EC, 2023a). A central, long-standing goal of the CAP is aligned with sustainable farm income and resilience of the farming sector across the European Union. The study concludes that the Common Strategic Plans (CSPs) prioritize targeted income support for farmers alongside initiatives to enhance productivity and encourage the adoption of innovative technologies. It suggests that the reformed CAP is poised to contribute to more substantial environmental and climate commitments while addressing the sustainable use of natural resources. This study also examines the decisions made by Member States in designing and allocating CAP interventions, evaluating their effectiveness in meeting Specific Objectives and analyzing the broader impacts of these decisions on EU agricultural policy, emphasizing the collective ambition and coordinated efforts among Member States. Key elements of the report have shaped the design and financial allocation of Direct Payments, Sectoral interventions, and Rural Development initiatives. Academic research highlights significant income disparities across the EU, which CAP aims to address through decoupled and coupled payments and support for Areas facing Natural Constraints (ANC). The policy seeks to enhance income redistribution from larger to smaller farms through Complementary Redistributive Income Support for Sustainability, supplemented by tools like payment reductions or capping for larger farms. The policy also prioritizes coupled support for economically, socially, or environmentally vital sectors.

3.2.11 European Technology Platform (ETP)

The ETP has developed a Strategic Research and Innovation Agenda titled "Food for Tomorrow's Consumer" to significantly enhance the innovation capacity and impact of the European food and drink industry, contributing to a sustainable food system (ETP "Food for Life," 2021). The strategy emphasizes funding innovative research programs that integrate omics technologies, which analyse data representing the structure and function of biological systems, with advanced big data analytics and establishing a strategic microbiology ecosystem. This will be achieved through partnerships with companies and institutions with cutting-edge expertise and resources. Such an initiative will facilitate the development of hierarchically organized, multiphase food structures designed to enhance the physiological action of various functional ingredients, mainly through novel processing and self-assembly techniques. Close collaboration with primary producers and product manufacturers is essential to make this structure-based health approach economically viable. The strategy also highlights the importance of developing technologies to enhance the collection, valorisation, and recycling of packaging materials and innovative packaging solutions that minimize food waste after initial use. Identifying and mapping new raw materials is a critical component of this process. In addition, food resilience systems should conduct detailed research into consumer perceptions of risk, food safety, and big food safety data in the marketplace, using post-launch monitoring approaches and combining these efforts with machine learning into new methods.

3.2.12 Circular Economy Action Agenda for Food

The "Platform for Accelerating the Circular Economy" (PACE) community has produced a report highlighting the importance of a circular economy in the food sector, emphasizing its potential to deliver significant benefits for human health and biodiversity (PACE, 2021). Circular strategies apply the principles of a circular economy to food system value chains with three clear objectives: producing food in ways that regenerate nature, ensuring food is not wasted, and utilizing commonly wasted resources productively. Essential steps are reframing wasted food and byproducts, facilitating the development and access to secondary markets, and establishing safe cycles for human waste management. Enhancing information accessibility and data utilization will further support these initiatives. An essential action for governments is to improve coordination and collaboration across ministries and departments related to agriculture, environment, health, trade, and business. To enable private sector innovation and action, governments should strengthen land governance mechanisms, realign agricultural subsidies toward nature-regenerative production methods, and set binding food waste reduction targets with investments in their achievement. Additionally, incorporating circularity into public procurement criteria, implementing landfill bans on food waste, and establishing nutrient management regulations in partnership with private sector stakeholders are critical measures to promote sustainable food systems.

3.2.13 Food 2030 Research and Innovation (EU)

The Food 2030 initiative is a strategic effort by the European Union to transform food systems and address the pressing challenges of sustainability, resilience, and health (EC, 2023b). It emphasizes collaboration and co-creation across all food system sectors, aiming to foster greater coherence from farm to fork within a robust research and innovation (R&I) framework. Aligned with crucial EU policies like the European Green Deal, the Farm to Fork Strategy, and the Biodiversity Strategy, the initiative seeks to promote sustainable agricultural practices, reduce food waste, enhance transparency, and encourage responsible consumption patterns. Food 2030 also recognizes the importance of aligning R&I efforts with the renewed European Research Area (ERA) and the EU's circular and sustainable Bioeconomy Strategy. It aims to leverage investments from Horizon Europe and the Next Generation EU Recovery Package to tackle immediate challenges heightened by the COVID-19 pandemic while preparing for a more sustainable future. By involving diverse stakeholders, including governments, industry, and civil society, Food 2030 drives policy reform, fosters innovation, and develops disruptive technologies that can profoundly transform food systems for sustainability, health, and inclusion. This multi-actor approach aims to create food systems that are environmentally friendly, socially equitable, and economically viable, both in Europe and globally.

3.2.14 European Partnership on Safe and Sustainable Food Systems for People, Planet and Climate (SSFS)

The SSFS is essential for transforming food systems to ensure environmental, social, and economic sustainability. Research and innovation are pivotal in this transformation, requiring collaboration among policymakers, businesses, researchers, and civil society. The SSFS partnership aims to coordinate European and national R&I efforts to future-proof food systems by fostering inclusive governance and strengthening science-policy-society interfaces. It will focus on four thematic areas: changing eating habits, improving production and processing methods, enhancing citizen engagement with food production, and promoting effective governance. The partnership seeks to accelerate the transition towards safe and sustainable food systems in Europe through joint funding, a food-systems observatory, a knowledge hub, and knowledge transfer initiatives (EC, 2021a).

3.2.15 Recipe for Change: An Agenda for Climate-Smart and Sustainable Food Systems (EU)

This report highlights the urgent need for Europe to address the interconnected challenges facing its food system, emphasizing sustainability, public health, and climate change resilience. It underscores the European Commission's FOOD 2030 initiative prioritizes nutrition, environmental sustainability, circularity, and community empowerment. Aligned with the Sustainable Development Goals and commitments under the Paris Agreement, Europe must transform its food system to be more sustainable, resilient, and inclusive. This transformation requires a holistic approach recognizing the interdependence of food production, consumption, land use, and environmental impact. Government intervention and supportive policies are essential to incentivize innovation and promote sustainable practices across the food supply chain. A mission-oriented approach is advocated to drive targeted solutions, such as improving dietary patterns, promoting healthy aging, and enhancing food processing.

Overall, concerted efforts are needed to ensure a healthy, equitable, and environmentally sustainable food system for Europe's future (EC, 2018).

3.2.16 Risks and Vulnerabilities in the EU Food Supply Chain (EU)

The study entitled "Risks and vulnerabilities in the EU food supply chain" surveyed stakeholders to comprehensively assess perceived risks and vulnerabilities in the EU food supply chain. It revealed a landscape marked by volatility, uncertainty, and crisis fatigue, with recent events like the COVID-19 pandemic and Russia's invasion of Ukraine underscoring the disruptive potential of unforeseen challenges. Economic, environmental, and market risks were most frequently identified, with emerging concerns like cybersecurity and climate-related risks gaining traction. Regional variations were notable, with southern and eastern Member States facing distinct challenges. Stakeholder perceptions varied by business size and type, highlighting differing concerns. Vulnerabilities were identified across various factors, with no single factor standing out significantly. The study's findings lay the groundwork for formulating strategies to address risks and vulnerabilities, emphasizing the need for coordinated, adaptable approaches that account for the diverse risk landscape and leverage existing EU policies to enhance food system sustainability and resilience (Bertolozzi-Caredio et al., 2023).

3.2.17 Sustainable Food System Framework Initiative (EU)

As the Inception Impact Assessment outlines, this initiative addresses unsustainable food production and consumption within the EU, aligning with the European Green Deal (EC, 2021b). It recognizes the interconnectedness of environmental, health, and social factors, emphasizing the need for a resilient, sustainable recovery plan in the wake of COVID-19. Guided by the Farm to Fork and Biodiversity Strategies, the initiative tackles critical issues such as pollution, biodiversity loss, and food waste driven by regulatory and market failures. The proposed objectives include promoting sustainable production, reducing waste, enhancing transparency, and fostering responsible consumption patterns. The legal basis for intervention is rooted in Articles 43(2), 114, 168(4)(b), and 192(1) of the Treaty on the Functioning of the European Union (TFEU: a foundational legal document that outlines the roles, powers, and functioning of the EU and its institutions), with policy options ranging from voluntary approaches to new comprehensive framework legislation. Expected impacts encompass economic, social, and environmental dimensions, with short-term costs mitigated by long-term benefits like innovation and resource efficiency. The initiative's implementation will require adjustments at both EU and national levels, focusing on minimizing administrative burdens and engaging stakeholders for effective policymaking. The objective is to create a sustainable and resilient food system across the EU.

3.2.18 Everyone at the Table: Co-creating Knowledge for Food Systems Transformation (EU)

The European Commission convened a High-Level Expert Group (HLEG) to assess the requirements and possibilities for enhancing science-policy interfaces to improve food systems governance. Acknowledging the urgent need for food system transformation exacerbated by the current crisis sparked by the Ukraine invasion, the HLEG emphasized the necessity for ambitious, interconnected science-policy-society interfaces. While existing elements of these interfaces are present, the HLEG identified significant gaps. The group's recommendations include urging multilateral governance organizations like the European Commission and the UN to adopt a comprehensive food system lens, engaging stakeholders at all levels and regions. Furthermore, it suggests enhancing the global science-policy-society interface landscape to integrate a broader range of voices, data, trends, and standards. To achieve these goals, the HLEG proposes three pathways: 1) adapting the current landscape with additional resources and broader mandates, 2) enhancing it with multisectoral task forces, and 3) coordinating agendas through a 'network of networks' facilitated by a global coordination hub invested in by various multilateral institutions (EC, 2021c).

3.2.19 Global Food Security Index (Economist Group)

The Economist Group, a global media and information services company, via its "Economist Impact Division," has established a valuable source of intelligence on global food security drivers. Specifically, the "Global Food Security Index (GFSI)" is a premier intelligence report, utilizing a dynamic transformation adopting circular agrifood systems and implementing climate-resilient practices such as crop rotation, permaculture, intercropping, and agroforestry (Economist Impact, 2022). It prioritizes implementing practical solutions that enhance natural resource management, ensure water and high-quality soil access, and scale rapidly to meet growing demands. Market-based incentives are critical for financial support, emergency funding, and partnerships tailored to local ecosystems. Strategies should include innovative land management, increasing soil organic carbon content, sustainable sourcing, improving energy efficiency, and reducing pollution, food waste, and post-harvest losses. Governments and NGOs should promote humanitarian measures such as price controls, the release of strategic reserves, and foreign aid.

Additionally, governments should coordinate risk management efforts and introduce environmental, economic accounting, and reporting requirements. Farmers must have access to agricultural inputs, financial products, and local knowledge providers, including extension services, cooperatives, and research institutes. They should also have access to food delivery services, digital equipment-sharing platforms, and low-cost micro-innovations at the local level to support their operations and improve food security.

3.2.20 The Economics of Food System Transformation. Global Policy Report (FSEC)

The Food System Economics Commission developed the "Global Policy Report" to evaluate strategies for comprehensively transforming the global food system (Ruggeri et al., 2024). Food system innovation is advancing unprecedentedly, with new technologies emerging across various domains, from Artificial Intelligence (AI) and sustainable processing methods to dietary additives for livestock and enhanced fertilizers. The report advocates for the modernization of plant breeding in low- and middle-income countries and the adoption of advanced digital tools such as satellite imaging, remote sensing, and in-field sensors to substantially enhance precision farming for smallholder farmers. Developing clean cold chains using efficient, zero-emission cooling technologies is essential to reducing post-harvest losses. The report stresses the need for governments to ensure that new and existing food system policies are coherent and fully aligned. By utilizing "policy bundles," governments can enhance synergies between various interventions, mitigate adverse effects, and align with broader transformations in other sectors. It is essential to focus policy efforts on areas of the food system where they will have the most significant impact. Furthermore, governments should coordinate food system reforms by establishing mechanisms that connect various government departments, levels of government, and critical stakeholder groups while applying an inclusion lens to policy design to ensure that reforms are equitable and broadly beneficial (Nordhagen et al., 2024).

3.2.21 Global Food Security (USNIC)

USNIC has produced a report to address the Intelligence Community's Assessment of global food security (NIC, 2015). The report outlines strategic baselines to supplement traditional approaches with less conventional methods, such as generating off-farm income activities, researching minor crops, and advancing technical education in agriculture. Emerging economies with growing expertise in food security can offer solutions to countries with low levels of development and technology. The report advocates enhancing food resilience by creating multiplier effects through complementary initiatives. These include integrating infectious disease control with food security programs and combining improvements in sanitation infrastructure with increased food production. Measures such as controlling human contagious diseases, conducting media education campaigns for consumers, and improving storage and transportation methods can mitigate food losses. The report emphasizes the need to support national and local governments in building reserve stocks, particularly in countries with high temperatures and unpredictable rainfall, and favouring container shipping over bulk shipping. Additionally, it is crucial to build government capacity to provide legal, administrative, and regulatory support for the food sector to bolster food security. The report also recommends maintaining agricultural commodity prices and adopting climate-smart agriculture practices, precision agriculture, drip irrigation, minimal or no-till farming, mixed cropping, and multipurpose trees and crop rotations.

3.3 European Union Legislative instruments

This section outlines the relevant European Union Directives, Regulations, and other initiatives influencing the region's food security approach. Given the complexity of the food sector, which encompasses multiple domains, authorities should consider all pertinent information to improve food sustainability within their countries. This approach should reflect their systems' specific challenges, concepts, and characteristics. This section presents the critical European legislative instruments and policies for SecureFood development.

3.3.1 “General Food Law” Regulation (EC) No 178/2002

Regulation (EC) No 178/2002, also known as the General Food Law Regulation, lays down the general principles and requirements of Food Law within the European Union (EC, 2002). It establishes common principles and responsibilities, the means to provide a solid scientific base, and efficient organizational arrangements and procedures to support decision-making in food and feed safety matters. This regulation applies to all food and feed production stages, processing, and distribution. Still, it does not apply to primary production for private domestic use or food preparation, handling, or storage for private domestic consumption. One of its key elements is establishing a risk analysis framework, which consists of three interconnected components: risk assessment, risk management, and risk communication. It also introduces the precautionary principle, allowing for protective measures to be taken when scientific evidence is inconclusive but potentially harms public health. The regulation establishes the European Food Safety Authority (EFSA), an independent agency funded by the EU, responsible for providing scientific advice and support to EU institutions and Member States. EFSA plays a crucial role in risk assessment, helping to ensure that food produced, processed, and sold within the EU is safe for consumption. The regulation assigns primary responsibility for food safety to food and feed business operators, who must ensure that their products are safe and comply with the requirements laid down in the regulation. It also mandates that food and feed must be traceable at all production, processing, and distribution stages. This traceability allows for quick and efficient identification and withdrawal of food or feed products that may pose a risk to public health. It outlines the main pillars for setting emergency measures for food and feed of Community origin or imported from a third country, as well as the development of a general plan for crisis management. Moreover, it establishes a rapid alert system for the notification of a direct or indirect risk to human health derived from food or feed, supporting effective crisis management and the exchange of information between EU Member States and the Commission in cases of emergencies.

3.3.2 Directive (EU) 2022/2557 on the Resilience of Critical Entities

Directive EU 2022/2557 mandates that each Member State shall adopt by 17 January 2026 a 'strategy' to enhance critical entities' resilience (EC, 2022a). This 'strategy' should encompass main elements regarding the delineation of objectives and priorities for improving critical entities' overall resilience, taking into account cross-border dependencies and interdependencies; the development of a structured governance framework to achieve the set strategic objectives, including the roles and responsibilities of the different competent authorities, stakeholders and critical entities involved; as well as the description of appropriate measures necessary to enhance resilience including 'Member States Risk Assessments' for sector-specific critical entities. Moreover, Member States shall ensure that within their territory, the critical entities are identified and shall carry out risk assessments to evaluate all relevant risks (man-made and natural) that could disrupt the provision of their essential services ('critical entity risk assessment'). Each critical entity shall implement appropriate and proportionate technical, security, and organizational measures to address risks and document relevant information in a so-called 'resilience plan.' It should also designate a liaison officer as a contact point. In case of an incident that can potentially disrupt the provision of its essential services significantly, the critical entity shall submit an initial notification to the competent authority within 24 hours. A Critical Entities Resilience Group also supports cooperation among national competent authorities, while information exchange is foreseen with Dir. 2022/2557 relevant authorities with particular reference to cybersecurity risks. Furthermore, critical entities of particular European significance shall be identified, and the Commission shall ensure that they receive appropriate support in meeting relevant obligations via the organization of advisory missions, which, among others, should also assess foreseen measures and report relevant findings to the Commission and the involved Member States.

3.3.3 Safeguarding Food Security and Reinforcing the Resilience of Food Systems- COM/2022/133

The European Commission's 2022 Communication addresses the urgent need to ensure food security in the EU amidst rising global challenges such as the COVID-19 pandemic, climate change, and geopolitical tensions, particularly the war in Ukraine (EC, 2022b). The document emphasizes the critical importance of maintaining a stable food supply for EU citizens while protecting food affordability, especially for vulnerable populations, as food prices rise due to disruptions in global markets. The Communication highlights the necessity of bolstering the resilience of EU food systems to better withstand future shocks by diversifying supply chains, promoting sustainable agricultural practices, and investing in innovation and research.

Aligned with the EU's Green Deal and Farm to Fork Strategy, the Communication advocates for a transition towards more sustainable food systems that minimize environmental impact, enhance biodiversity, and address climate change. It underscores the essential role of farmers and rural communities in maintaining food security and outlines support mechanisms through the Common Agricultural Policy (CAP) and Common Fisheries Policy (CFP). The CAP Strategic Plans will prioritize reducing dependency on external inputs like gas, fuel, pesticides, and fertilizers, supporting sustainable biogas production, precision farming, carbon farming, and agroecological practices. These efforts will be undertaken while ensuring the implementation of adequate social protection systems and access to essential services in full compliance with data protection principles and the free movement of such data within the European Union (EC, 2016). Additionally, social protection systems and access to essential services will be strengthened for vulnerable groups.

International cooperation is another focal point of Communication, as global food security is increasingly intertwined with EU food systems. The EU aims to assist developing countries in building resilient agricultural systems and ensuring fair trade practices. The document also emphasizes the importance of solidarity with Ukraine, mainly by providing food aid and supporting its agricultural and fisheries sectors. Additionally, the Commission encourages Member States to monitor food prices, support debt relief for green recovery, and increase humanitarian aid to regions most affected by food insecurity.

The Russian invasion of Ukraine has intensified global agricultural instability, driving up energy and fertilizer costs and directly impacting food prices in the EU. The war has disrupted trade in cereals and oilseeds from the Black Sea region, posing significant risks to global food security. Although the EU remains self-sufficient in many agricultural products, it relies on imports for specific items such as feed protein, sunflower oil, and seafood. This reliance has exposed vulnerabilities in the supply chain, particularly as rising production costs may hinder the availability of affordable food.

In response, the Communication outlines several short-term and long-term strategies. Immediate measures include reducing demand for fuel and feed, encouraging higher wheat plantings, and providing a €500 million support package for farmers affected by the Ukraine conflict. Market safety nets and adjustments to greening obligations are also proposed. In the long term, the EU is committed to reducing dependency on fossil fuels and imported agricultural inputs, focusing on sustainable fertilizer production and promoting plant protein alternatives.

The Communication concludes by reaffirming the EU's commitment to building a more resilient and sustainable food system. By investing in sustainable practices, promoting innovation, and ensuring effective social protection measures, the EU aims to safeguard food security for all its citizens while addressing the growing global challenges posed by geopolitical conflicts, climate change, and economic disruptions. The Commission also stresses the need for ongoing collaboration with international partners to tackle food security challenges on a global scale.

3.3.4 Contingency Plan for Ensuring Food Supply and Food Security in Times of Crises- COM/2021/689

The European Commission's "Contingency Plan for Ensuring Food Supply and Food Security in Times of Crises" (COM/2021/689) is a strategic framework aimed at addressing weaknesses revealed by recent crises, notably the COVID-19 pandemic (EC, 2021d). It is designed to strengthen crisis preparedness, bolster resilience, and ensure the stability of the food supply in the face of future disruptions. The plan focuses on maintaining a reliable food supply across the EU, recognizing that any disruptions can lead to significant social and economic impacts. It emphasizes enhanced coordination between EU Member States, non-EU countries, and key stakeholders across the food supply chain, fostering improved collaboration between public and private sectors.

A central feature of the plan is the establishment of the European Food Security Crisis Preparedness and Response Mechanism (EFSCM). This mechanism comprises a dedicated expert group that meets regularly and during emergencies to assess risks and manage large-scale events threatening the food supply. The EFSCM focuses on identifying vulnerabilities in food value chains, conducting stress tests, and proposing recommendations for crisis management. Member States are encouraged to develop and share national contingency plans, enhancing overall preparedness. The plan also promotes international cooperation, mainly through the Agricultural Market Information System (AMIS), to improve global food security efforts.

The communication highlights the need to improve EU-wide coordination in food-related crises, aiming to prevent a recurrence of issues seen during the COVID-19 pandemic. During that period, supply chain disruptions caused temporary shortages and increased market instability, underscoring the necessity for structured crisis response mechanisms. The plan draws on lessons from this experience, emphasizing the importance of uninterrupted trade, the free movement of goods, and the role of transport and logistics sectors in maintaining food security.

Additionally, the plan aligns with the EU's broader sustainability objectives, such as the Farm to Fork and Biodiversity Strategy. It seeks to enhance the resilience of food systems while promoting sustainable agriculture and fisheries. The Common Agricultural Policy (CAP) and the Common Fisheries Policy (CFP) are vital tools in supporting this transition, with provisions for financial assistance and regulatory flexibility during crises.

International cooperation is also a significant focus, as food security is increasingly affected by global market dynamics. The plan emphasizes the importance of collaboration with global initiatives and partners, aiming to mitigate the effects of supply disruptions, trade restrictions, and dependencies on non-EU imports, particularly in critical sectors like oilseeds and fish products.

3.3.5 The European Green Deal-COM/2019/640

The European Green Deal outlines a transformative strategy to achieve a fair, prosperous society with a competitive, resource-efficient economy that reaches net-zero greenhouse gas emissions by 2050 (EC, 2019). It prioritizes protecting natural capital and citizens' health from environmental risks across the energy, industry, transport, and agriculture sectors. Key actions include introducing a 'Climate Law' to align all policies with climate neutrality, increasing 2030 emission reduction targets, implementing effective carbon pricing, and proposing a carbon border adjustment mechanism. Moreover, the Farm to Fork Strategy consists of one of the critical pillars of the Green Deal, putting at the front line the development of strategic plans reflecting the ambition to reduce the use and risk of chemical pesticides, fertilizers, and antibiotics. The Green Deal emphasizes decarbonizing the energy sector through renewable sources and phasing out coal while supporting Member States' ambitious energy and climate plans. It also focuses on smart infrastructure, mobility, sustainable transport fuels, consumer involvement in clean energy, and transitioning industries towards sustainable practices. It includes a circular economy action plan targeting reusable packaging and biodegradable plastics by 2030.

3.3.6 A Farm to Fork Strategy-COM/2020/381

The Farm to Fork Strategy is a core element of the European Green Deal, aiming to create a fair, healthy, and environmentally friendly food system in the EU (EC, 2020a). It addresses the entire food chain, from production to consumption, to ensure food security, reduce environmental impact, and promote sustainable practices. The strategy focuses on reducing pesticide use, enhancing animal welfare, promoting organic farming, improving the availability and price of sustainable food, reducing food waste, and encouraging healthier diets by empowering consumers to make informed and sustainable choices. In parallel, a zero-tolerance policy for food fraud is set in place along the entire food supply chain. The Commission shall work with Member States to strengthen the role of the European Innovation Partnership. At the same time, the European Regional Development Fund is foreseen to invest in innovation and collaboration along the food value chains. The EU will also pursue the development of Green Alliances on sustainable food systems with all its partners in bilateral, regional, and multilateral fora, including cooperation with Africa, neighbours, and other partners. By 2030, it aims to make Europe's food system more resilient, minimize its carbon footprint, and contribute to global food security while supporting farmers and ensuring fair economic growth. The ultimate goal of this strategy is to make the EU food system an international standard for sustainability.

3.3.7 EU Biodiversity Strategy for 2030-COM/2020/380

The European Commission has adopted the new 'EU Biodiversity Strategy' for 2030 and an associated Action Plan, which involves a comprehensive, ambitious, long-term plan for protecting nature and reversing the degradation of ecosystems (EC, 2020b). It aims to put Europe's biodiversity on a path to recovery by 2030, benefiting people, the climate, and the planet. Actions focus on restoring 10% of agricultural land to diverse landscapes and increasing organic farming to 25% by 2030. It advocates for a new EU Forest Strategy to plant 3 billion trees, emphasizing marine and freshwater ecosystem restoration. The strategy integrates urban greening and pollution reduction plans, including a Zero Pollution Action Plan.

Additionally, it seeks to mobilize public and private funding for biodiversity, strengthen global governance, and integrate biodiversity considerations into all EU policies. Globally, the EU aims to lead in biodiversity conservation, support sustainable development, combat illegal wildlife trade, and promote biodiversity-friendly practices through partnerships and financing. Puts as a priority the enhancement of societies' resilience to future threats such as climate change impacts, forest fires, food insecurity, or disease outbreaks, including wildlife and fighting illegal wildlife trade protection. As a core part of the European Green Deal, the Biodiversity Strategy also supports a green recovery following the COVID-19 pandemic.

3.3.8 Blue Economy Strategy-COM/2021/240

The European Commission's 2021 Communication titled "Transforming the EU's Blue Economy for a Sustainable Future," also known as the Blue Economy strategy, provides a comprehensive maritime policy agenda for the next decade (EC, 2021a). This strategy supports the transition outlined by the European Green Deal within the ocean economy, emphasizing the need to achieve carbon neutrality by developing offshore renewable energy and decarbonizing maritime transport and ports. It also addresses reducing marine pollution, promoting recycling solutions, and prioritizing marine biodiversity preservation and restoration. In addition, the strategy outlines actions to support climate adaptation efforts, including developing green infrastructure in coastal regions, conserving biodiversity and coastal ecosystems, and enhancing sustainable tourism and coastal economic development. By improving the sustainable use of marine resources and encouraging alternative food and feed sources, the Blue Economy can alleviate pressures on climate and natural resources involved in food production. This Communication further emphasizes the need to enhance the resilience of a sustainable blue economy by deepening scientific understanding of the ocean and its ecosystems, ensuring free access to relevant data, promoting marine and maritime research and innovation, and mobilizing investment through private capital, EU public funding, and cohesion policy resources. Additionally, the strategy underscores the importance of building a highly skilled workforce with advanced technological expertise and enhancing public perception of careers in the blue economy. Finally, the strategy highlights the necessity of widely accepted frameworks and conventions in maritime spatial planning, fostering citizen engagement, promoting cooperation at the regional level, strengthening maritime security, and advancing international maritime policy.

3.4 National Plans

Countries within and outside the EU have integrated national plans into their food security policies. In the following, some of these countries are examined as indicative and representative examples on a European and global scale.

3.4.1 Austria

The Federal Ministry of Agriculture, Forestry, Regions, and Water Management has developed the National Food Security Report to assess Austria's food supply situation in 2023 across the entire value chain, from the availability of operating resources to food processing and trade (Austrian MFA, 2023). The report emphasizes the importance of food security, highlighting the role of widespread family farm production, particularly in disadvantaged and mountainous areas. It also underscores the value of robust agricultural education, economic diversity in farming, sustainable practices that align with ecological and animal welfare standards, a sufficient number of domestic food producers, and the benefits of an open EU internal market. The report also addresses the development of agricultural production, considering factors such as climate change and land use, with future forecasts detailed in the "Green Report" every two years. Published annually by the Ministry, the "Green Report" provides an in-depth analysis of the state of Austrian agriculture and forestry. Austria is a leader in organic farming within Europe, with 27% of its land and 22.5% of its farms dedicated to organic practices. By 2030, the country aims to increase these figures to 30%, involving the entire value chain while continuing efforts to strengthen resilience measures.

3.4.2 Estonia

The government of Estonia has published an Agriculture and Fisheries strategy in cooperation with the Ministry of Rural Affairs. The Strategy outlines the need for viable rural and coastal communities, biodiversity-healthy environments, and thriving food businesses to enhance food security (Ministry of Rural Affairs of Estonia, 2021). The strategy will be implemented with public, private, and third-sector actors, with actions that meet all objectives. Key actions include producing high-quality products in an environmentally friendly way, cooperation within and between all food sectors, and using the latest research results and best technologies. Also, the strategy stresses the need for fertilizers and plant protection products, freedom from dangerous pests and animal diseases, diversity in the spectrum of arable and horticultural crop varieties and plant propagating material, consumers' high level of food safety awareness, competitive food sector in both the domestic and foreign markets, domestic food consume, active rural population, diversified businesses with growing added value in rural areas and knowledge transfer. Moreover, it focuses on managing fish stocks in an environmentally responsible and sustainable way, promoting environmentally conscious recreational fishing and fisheries, and aquaculture high-quality products with high added value and export potential.

3.4.3 Finland

Finland has crafted the Food Policy Report as an integral part of its national food policy, aimed at establishing the conditions necessary for the competitiveness and diversity of primary production, food safety, supply security, and the effective operation of the food industry (Ministry of Agriculture and Forestry of Finland, 2017). This report was prepared with various stakeholders and the Ministry of Agriculture and Forestry. To achieve the objectives of this unified food policy, it is essential that the government, parliament, and all actors within the food system are fully committed. The Finnish food policy focuses on responsible and sustainable food production and consumption, aiming to create a food system that contributes to financial and social well-being. Additionally, it promotes the concept of food citizenship, where citizens are not only informed about the health and safety aspects of food but also understand the broader quality factors associated with food production and consumption, including the right to food, food ethics, fairness, environmental impact, and cultural significance. This policy's key pillars include enhancing food appreciation, emphasizing consumer-centric food production, and fostering sustainable food systems that rely on domestic resources. The report also highlights the crucial role of the Finnish National Emergency Supply Agency (NESA) in ensuring supply security through financial and economic policies and contingency planning. NESA and the National Emergency Supply Organisation (NESO) facilitate industry-specific cooperation and joint exercises to prepare for emergencies. Critical industries are legally mandated to ensure operational continuity during crises, with government authorities granted the power to oversee essential functions. Additionally, businesses are foreseen to voluntarily contribute to supply security by utilizing NESA's continuity management tools and collaborating with public and private sectors to safeguard the national food supply.

3.4.4 Flemish Region of Belgium (Flanders)

The Flemish Agriculture & Fisheries Minister has developed the Flemish food strategy, aligning it with the European Commission's Food 2030 research policy framework. The strategy focuses on ensuring healthy and sustainable food, maintaining a food system within ecological limits, fostering a resilient food economy, and strengthening the connection between farmers and citizens (Go4Food, 2023). Local governments are tasked with advancing sustainable development within their territories. The Flemish government established the Food Policy Network to support this strategy, which promotes cross-sector collaboration on food-related issues. Implementing and embedding the strategy will require close cooperation with the food coalition and the Food Policy Network to develop a long-term roadmap, ensure structural integration, and establish effective monitoring and evaluation mechanisms. The strategy emphasizes the need for collective action among all social actors to guide a transformative process. It calls for measures to enhance systemic thinking, foster adaptive learning, and encourage collaboration across different sectors. This strategy is intended to be a cornerstone for developing local food policies.

3.4.5 France

France has formulated a comprehensive strategy for food security, nutrition, and sustainable agriculture in collaboration with the French Ministry for Europe and Foreign Affairs (MEAE). This strategy outlines France's action plans in food-related areas and provides clear guidance for future initiatives (French MFA, 2019). France's approach to food security includes international efforts under the Orientation and Programming Law on Development and International Solidarity Policy (LOP-DSI law) and the development of sustainable agri-food sectors aimed at creating decent jobs in rural areas, particularly for young people. The French government supports family farmers through the French Development Agency (AFD). It establishes and enhances cooperatives, which enable family farmers to foster equitable relationships with processing industries and, where necessary, to acquire their processing equipment.

Furthermore, the French government ensures the implementation of the Paris Agreement, the legally binding international treaty on climate change. A key initiative in this effort is the "4 per 1000: Soils for Food Security and Climate," which encourages stakeholders to transition toward regenerative, productive, and highly resilient agriculture based on sustainable land management practices. France leverages its research institutions and networks to provide technical expertise and offers financial and technical support through the French Facility for Global Environment (FFEM).

Additionally, it offers budgetary support for civil society organizations via MEAE and AFD. The strategy emphasizes the protection of legitimate land rights, adherence to the Voluntary Guidelines on the Responsible Governance of Tenure of Land, Fisheries, and Forests, and the promotion of equal access to resources and property for women. France also supports the Regional Sahel Pastoralism Support Project (PRAPS), which aims to enhance the productivity and resilience of pastoral communities' livelihoods. Through its programmed food assistance (PFA), France strengthens the resilience of populations to shocks that lead to food insecurity, whether in emergencies or chronic food insecurity.

3.4.6 Norway

The Norwegian Ministry of Foreign Affairs has developed a strategy to enhance food security within development policy, focusing on improving food self-sufficiency (Norwegian MFA, 2022). This strategy involves the coordinated efforts of civil society, farmers' and fishers' organizations, the private and public sectors, academic and research institutions, Norway's diplomatic missions, and multilateral partners in fostering food resilience. The strategy is grounded in the Sustainable Development Goals, climate targets, and international human rights instruments. It calls for proactive measures to strengthen food security through global leadership, increased food sovereignty, and enhanced dialogue with national authorities and multilateral organizations. A vital aspect of this strategy is emphasizing sustainable food systems, particularly for small-scale producers and climate-resilient food production, including nature-based carbon capture solutions. The plan prioritizes women's empowerment in small-scale food production by supporting reforms in business and regulatory frameworks, fostering the creation of women-led cooperatives and organizations for farmers and fishers, and requiring partners to prioritize gender equality.

Furthermore, governments should focus their efforts on sub-Saharan Africa by intensifying political dialogue with the governments of priority African countries, the United Nations, and development banks. The government is encouraged to promote locally produced school meals, strengthen early warning mechanisms, and support innovative financing models. Additionally, the Ministry of Foreign Affairs aims to enhance cooperation with UN food security organizations to ensure the effective coordination of humanitarian efforts and development assistance.

3.4.7 Scotland

The Scottish Government's Good Food Nation Plan sets out a comprehensive and collaborative strategy to achieve the nation's food-related goals, as formalized in the Good Food Nation (Scotland) Act 2022 (Scottish Gov., 2024; Scottish Gov., 2022). This plan requires Scottish Ministers to develop a national food policy with clear objectives and strategies. It also involves collaboration with the UK Food Data Transparency Partnership to enhance data collection for informed policymaking. Aligned with the second Scottish Climate Change Adaptation Programme (SCCAP), the plan addresses the impacts of climate change on domestic production and international food trade. Key initiatives include promoting healthy diets in educational settings, tackling food insecurity through the Dignity Report's recommendations, and boosting household incomes via fair work and social security measures. The plan also emphasizes the importance of sustainable farming practices through the Preparing for Sustainable Farming initiative, launched in 2022, which supports farmers in adopting environmentally friendly practices. This three-year program provides funding for on-farm carbon audits, soil sampling, and, for livestock keepers, interventions in animal health and welfare. Beginning in 2025, the Agricultural Reform Programme will transform agricultural support policy while supporting payments to farmers' efforts in achieving climate and nature objectives while continuing to ensure the production of high-quality food.

3.4.8 United Kingdom

The Department for Environment, Food & Rural Affairs (DEFRA) has formulated a comprehensive food strategy that includes policy initiatives to enhance the health, sustainability, and accessibility of diets while ensuring food supply security (UK DEFRA, 2022). This strategy underscores the importance of domestic producers and the industry in contributing to the government's levelling-up agenda. In alignment with the UK Food Strategy, the Economic and Social Research Council (ESRC) is funding a series of food system trials in 2023. The strategy highlights the need to sustain domestic agricultural production through productivity improvements and the adoption of new farming schemes, taking advantage of post-Brexit opportunities. It also emphasizes the role of new Free Trade Agreements (FTAs) made possible by Brexit, alongside Farming Innovation Programmes and United Kingdom Research and Innovation (UKRI)—furthermore, the strategy advocates for improvements in school food and a robust food curriculum. Key elements of the UK's evolving food policy include the implementation of Environmental Land Management schemes (ELMs) and the launch of the UK Food Data Transparency Partnership, which will focus on health metrics and sustainability reporting. Future initiatives, such as the Agricultural Model Intercomparison and Improvement Project (AgMIP), are expected to enhance the ability to assess and ensure future food security (UK HSA & DHSC, 2023).

3.4.9 Brazil

Brazil has established the National Plan for Food and Nutrition Security (PLAN 2016-2019), the primary instrument for implementing the National Food and Nutrition Security Policy (Caisan, 2016). This intersectoral plan is developed by the Interministerial Chamber for Food and

Nutritional Security. It is informed by the priorities set by the National Food and Nutritional Security Council, as derived from the National Conference on Food and Nutritional Security. Key initiatives under the plan include increasing the minimum wage, expanding social programs, and supporting family farming through programs such as the National Program to Strengthen Family Farming and public procurement initiatives, like the Food Acquisition Program and National School Feeding Program. The plan also outlines the creation of the National Food and Nutrition Security System, the enhancement of family farming, the fortification of agroecological production systems, and the implementation of agricultural commercialization policies, including the Policy of Minimum Price Guarantees. The plan also emphasizes technical cooperation rooted in the Human Right to Adequate Food and calls for establishing a monitoring system to oversee the National Food and Nutritional Security Policy.

3.4.10 Canada

The Government of Canada has developed the Federal Sustainable Development Strategy (FSDS), a comprehensive framework for advancing sustainable development through specific, measurable, and time-bound targets while promoting intergenerational equity (Gov. Of Canada, 2022). This strategy integrates and coordinates with principles outlined in "A Food Policy for Canada" and adheres to guidelines established by the Canadian International Development Agency (CIDA). The FSDS addresses invasive species management and enhances food security in Indigenous and remote communities through targeted financial assistance. The policy aims to improve food-related health outcomes and access to opportunities within the agriculture sector while advancing reconciliation with Indigenous Peoples. Additional programs supporting food security in Canada include a cross-government reporting framework, the Canadian Agricultural Partnership, and the Nutrition North Canada Retail Subsidy Program, which reduces the cost of nutritious food in 121 isolated communities. Social initiatives such as the Agricultural Clean Technology program aid farmers in adopting sustainable practices, while the Canada Child Benefit and Old Age Security programs enhance access to essential resources. In the future, the online version of the FSDS is foreseen to be regularly updated to incorporate new or revised targets, include results as data becomes available, and specify the actions federal organizations will undertake to support FSDS objectives.

3.4.11 India

The Government of India has enacted the National Food Security Act, which provides a comprehensive framework for ensuring food security for all citizens (Ministry of Law and Justice of India, 2013). This legislation mandates state governments to develop guidelines and identify eligible households. It outlines the central government's obligations and specifies the roles and responsibilities of state governments in implementing and monitoring food security programs. It includes provisions for eligible households to receive subsidized foodgrains under the Targeted Public Distribution System (TPDS). It provides nutritional support for vulnerable groups such as pregnant women, lactating mothers, and children, along with measures to prevent and manage child malnutrition. In addition, the framework establishes a grievance redressal mechanism, including appointing District Grievance Redressal Officers and State Food Commissions. Moreover, it assigns the implementation of the TPDS to local authorities, emphasizing their obligations while ensuring transparency and accountability by disclosing TPDS records, social audits, and establishing Vigilance Committees. Finally, the framework addresses the advancement of food security, explicitly targeting remote, hilly, and tribal areas, and outlines additional steps to enhance food and nutritional security.

3.4.12 Japan

The Ministry of Foreign Affairs and the Ministry of Agriculture, Forestry and Fisheries of Japan actively address global food security challenges through their Official Development Assistance (ODA) program, which prioritizes cooperation in agriculture, forestry, and fisheries, including the development of food value chains (Ministry of Foreign Affairs of Japan, 2024). The report highlights the need to improve emergency food assistance, safeguard citizens from radionuclide contamination in food, and support school feeding programs. It emphasizes the importance of encouraging local communities to engage in agricultural land development and social infrastructure through food distribution, thereby promoting self-reliance. The report also addresses the need for a robust food monitoring system to manage chemical hazards and pesticide residues, implement a traceability system for food origin, and establish an emergency response classification system [Ministry of Agriculture, Forestry and Fisheries of Japan, 2014]. It advocates for nutritional improvement programs in collaboration with private sector partners through initiatives like the Nutrition Japan Public-Private Platform (NJPPP). It aims to foster the establishment of global food value chains through public-private partnerships. Finally, the report underscores the enhancement of food security through multilateral cooperation, particularly by promoting the Responsible Agricultural Investment (RAI) initiative proposed by Japan. This initiative seeks to coordinate efforts and optimize benefits for the host country's government, local communities, and investors.

3.4.13 South Africa

The Government of the Republic of South Africa has developed, with the Department of Agriculture, Forestry and Fisheries, a National Food and Nutrition Security Policy that aims to enhance existing initiatives through improved alignment, coordination, and oversight (DAFF of South Africa, 2014). It emphasizes measuring food and nutrition security at individual and national levels, proposes a centralized food safety and quality control system, and supports regional development through investments in agricultural infrastructure, institutional reform, and potential Regional Food Reserves. Leadership will be provided through partnerships among public, private, and civil society sectors. Key pillars are nutritional safety nets, nutrition education, agricultural investments aligned with local economic development, market participation for emerging agricultural sectors through public-private partnerships, and practical food and nutrition security risk management. Following this Policy, the Government established a National Plan, whose principles are aligned with 17 key indicators, leveraging existing departments and introducing new initiatives such as enhanced nutrition training and nutrition-sensitive public works programs. It emphasizes high-level governmental responsibility for nutrition improvement and advocates for establishing a council and forums to facilitate participatory planning and reporting. The plan also calls for increased public research funding to evaluate its components and prioritize research on health, nutrition, food security, and social policy (Gov. of South Africa, 2017).

3.4.14 United Arab Emirates

The Mohammed Bin Rashid School of Government, a leading institution in public policy research and education in the Arab world, has developed a report to introduce best practices and provide recommendations for improving food security (MBRSG, 20183). This report is based on benchmarking policies from countries facing similar challenges. It emphasizes the need for government, universities, the private sector, and industry collaboration to implement long-term national strategies. Key recommendations in the report include the development of a robust agricultural sector investment in innovative farming techniques such as soilless farming, hydroponics, advanced greenhouse methods, and dry agro-technologies. It advocates for creating national frameworks that promote public-private partnerships and the cultivation of resilient, high-value crop strains. The report also highlights the importance of enhancing the UAE's food import system by lowering import tariffs, optimizing the re-export system, and supporting a diversified food import policy. It calls for maintaining food price controls, fixed pricing for staple foods, and ensuring a six-month supply of food stocks.

Further support is recommended for the Abu Dhabi Food Security Centre (ADFSC), which provides initiatives such as a "Minimum Price Guarantee" (MPG) for farmers and the Food Security Dashboard, which monitors five key food security indicators. Furthermore, the report mentions an initiative undertaken during a food crisis in the UAE, which involved purchasing or leasing land abroad, particularly in neighbouring regions such as East Africa. Future steps for the UAE should include a large-scale national food waste awareness campaign, developing targeted food production strategies for staple foods, and training farmers in advanced agricultural technologies and methods.

3.5 Regional Practices

Aiming to ensure food security, different practices have been developed by European and international organizations with applications in other continents and regions. By these means, the primary strategies applied to manage challenges, threats, and future needs in diverse socioeconomic and political landscapes are outlined to emphasize the importance of adopting a holistic approach while formulating food systems resilience frameworks.

3.5.1 Belgium

The European Commission's Aquaculture Assistance Mechanism supports EU Member States, the EU aquaculture industry, and other relevant stakeholders in implementing the "Strategic guidelines for a more sustainable and competitive EU aquaculture." Through its multi-annual National Strategic Plans for developing sustainable aquaculture from 2021 to 2030, the Commission has proposed several strategic initiatives for EU member countries. An indicative reference regards the "Belgian Strategic Plan for Aquaculture 2021-2030" (EC, 2023c). This plan aims to enhance the resilience of the food supply in Belgium's primary aquaculture regions, Wallonia and Flanders. Wallonia primarily focuses on semi-intensive or extensive production sites and has micro aquaculture sectors involving minimal volumes. In contrast, Flanders predominates in land-based aquaculture using Recirculating Aquaculture Systems (RAS).

The plan encourages sector development and entrepreneurship, optimizing innovative and sustainable production methods, addressing judicial bottlenecks, and maintaining artisanal aquaculture in Wallonia. In Flanders, financial support encompasses a range of aquaculture-related activities aimed at promoting entrepreneurship, fostering networking, enhancing knowledge exchange, driving innovation, and ensuring the sustainability of aquaculture enterprises. This support is provided within broader frameworks, including Interreg, the Blue Cluster partnership, and Flanders Innovation & Entrepreneurship, which offer innovation grants. Meanwhile, operators in Wallonia's commercial fisheries sector can access support from the Public Service of Wallonia for "Economy, Employment, and Research," as well as public financial assistance covering all 11 agricultural sectors in Wallonia. The Framework Agreement for the Management Board of Producers references the European Maritime, Fisheries, and Aquaculture Fund as a complementary funding source, facilitating practical applications and entrepreneurship from research and innovation.

3.5.2 Ukraine

The non-governmental organization "Analytical Center of the Agrarian Union of Ukraine," prepared a document within the framework of the project "Supporting the Activities of the UNP EaP in 2021-2023" to address food security and food safety during and after the war (Analytical Center of the Agrarian Union of Ukraine, 2022). The report emphasizes that the key elements of post-war development should build upon the successes of the "Paths of Solidarity" initiative. During the war, it is deemed essential to impose a moratorium on government inspections of food safety while restoring the activities of control bodies responsible for state, market, and metrological supervision. Additionally, it is crucial to establish a robust consumer rights protection system and an effective mechanism for regulating the circulation of food products. In the post-war recovery phase, a fundamental initiative is to conduct extensive educational campaigns to inform consumers about the hazards related to counterfeit products and to educate market stakeholders on tools and procedures to combat counterfeiting. Critical components of this recovery action include creating a reconstruction platform, establishing a National Standardization Body, implementing educational programs for food specialists in schools, and developing tools for information dissemination and open discussion. Moreover, it is believed that a unified quality infrastructure system will significantly contribute to creating a robust agricultural sector, enhance the capabilities of food market operators, increase export potential, and stabilize foreign trade.

3.5.3 African Union

The African Union's Climate Change and Resilient Development Strategy and Action Plan (2022-2032) outlines priority interventions and recommended actions to secure food systems in response to climate change (AU, 2023). A national plan should promote the equitable sharing of climate risk and reward among all food system actors, mainly small-scale rural farmers, by establishing a regional climate-risk insurance facility. Policies should be modified to become more inclusive and participatory, supporting sub-national scales of food systems governance. Key actions include implementing an appropriate valuation framework for farmers' ecosystem management services, ensuring fair compensation, transitioning to agroecological production systems, and reducing dependencies on external inputs. This can be achieved by supporting research, extending public sector initiatives, utilizing market-based instruments to promote indigenous agroecological approaches, and providing resources to facilitate the transition to more nature-positive production systems. It also focuses on the role and influence of public procurement to support diverse and nutritious diets, such as through municipal support for local sourcing to public canteens and home-grown school feeding programs. The plan suggests synergies across sectoral planning, investments in infrastructure, and related areas, as well as aligning food system targets with other national strategies and commitments. At the same time, it is essential to strengthen finance, investment, and resource allocation interventions to support these initiatives.

3.5.4 Australia

The Australian Parliament's Committee on Agriculture has recommended the creation of a comprehensive National Food Plan, emphasizing clear objectives and measurable targets, supported by regular updates and action plans (House of Representatives Standing Committee on Agriculture, Australia, 2023). The plan should involve collaboration among federal, state, territory, and local governments to safeguard agricultural land from urban sprawl and non-agricultural use. Historical policies have shaped Australia's food policy, including the Australian Food and Nutrition Policy (1992), the National Food Plan (2013), and CSIRO's 2023 report. The proposed National Food Security Strategy aligns with the UN Sustainable Development Goals, aims to protect domestic food security, enhance global exports, and incorporate climate change mitigation measures. Key elements include prioritizing "First Food Security" for infants and young children, involving First Nations Peoples in land and ecosystem management, and establishing an Industry Advisory Group for risk mitigation. Recommendations include legislating the Right to Food, instituting regular data collection on food security using the United States Department of Agriculture (USDA), considering a Minister for Food position, and maintaining the GST exemption for fresh produce. The strategy sets 2030 targets to halve food waste, reduce losses along the supply chain, and ensure equitable access to nutritious, sustainably produced food. It also supports Australia's goal of achieving net-zero emissions by 2030 and enhancing food systems' resilience to evolving risks and stressors.

3.5.5 China

The Center for Strategic & International Studies (CSIS) examines China's food security challenges, focusing on its limited arable land, inefficient agricultural practices, environmental degradation, and dependency on global supply chains. It underscores food security's historical and strategic significance for China's national stability, social cohesion, and economic resilience. Under President Xi Jinping, food security has become a priority, with efforts to achieve agricultural self-sufficiency, improve sustainability, and diversify supply chains to mitigate geopolitical risks. Key policies include land reclamation, rural revitalization, technological innovation, and strict food safety regulations. The study highlights changing dietary preferences among China's growing urban middle class, climate change impacts, and workforce shortages in agriculture as additional hurdles. It also explores China's global role, including international collaborations and initiatives like the Belt and Road to enhance agricultural inputs. The analysis emphasizes the implications of China's food security strategies for domestic stability and the global food system.

3.5.6 New Zealand

The Ministry for Primary Industries outlines New Zealand's strategic intentions for the food and fiber sector, emphasizing enhancing regulatory systems across agriculture, forestry, fisheries, food safety, biosecurity, and animal welfare (MPI of New Zealand, 2021). The Ministry collaborates closely with central and local government agencies, indigenous organizations, private sector entities, and key stakeholder groups to achieve these goals. The policy aims to achieve four key outcomes: Prosperity, Sustainability, Protection, and Visible Leadership. Key actions include improving nutritional safety nets, better nutrition education, and investing in sustainable agricultural practices. The strategy emphasizes sustainable land use, climate change mitigation, and protecting natural resources. It prioritizes food safety, ethical production, and robust biosecurity measures. Partnerships with Māori, industry, and government are essential for fostering innovation and regional development. The policy supports workforce development, creating a centralized food safety system to ensure a resilient, thriving, and sustainable food sector.

3.5.7 United States

The Food Law and Policy Clinic, in collaboration with the Center for Agriculture and Food Systems, published "The Urgent Call for a U.S. National Food Strategy" in October 2020, presenting a comprehensive roadmap for developing a U.S. national food strategy.

Additionally, the U.S. Government's Global Hunger & Food Security Initiative has released the U.S. Government Global Food Security Strategy for 2022-2026 under the Feed the Future program. The first document suggests that a national food strategy should designate a leading office or agency to draft and implement the strategy, convene an interagency working group with representatives from all relevant federal agencies, and facilitate effective communication with stakeholders. Significant opportunities for broad-based public input should be created through the strategy development process, ensuring extensive stakeholder engagement and public participation. Additionally, the process should involve publishing a detailed written strategy plan, accompanied by the so-called "public facing" progress reports. To ensure the strategy's durability, periodic revisions and updates are essential to reflect evolving circumstances (FLPC, 2020).

Furthermore, the U.S. government supports a comprehensive global food strategy that focuses on strengthening productive and inclusive food systems, enhancing access to markets and trade, promoting employment and entrepreneurship, boosting sustainable productivity, and improving proactive risk reduction and management practices. The strategy should also focus on enhancing adaptation to and recovery from shocks and stresses, increasing the consumption of nutritious foods, promoting more hygienic environments, and strengthening commitments to food security investments. The global strategy should emphasize increased gender equality and youth livelihoods, enhanced climate change adaptation and mitigation, and improved natural and water resource management. Furthermore, it should ensure more effective governance, policies, and institutional operations, enhance human, organizational, and system performance, and integrate conflict sensitivity and social cohesion (Feed the Future, 2021).

3.6 Standardization Landscape

Harmonization and uniformity in the activities involved are essential for creating an environment driven toward excellence in the food sector. Therefore, exploring the current standardization landscape and implementing best practices in the food sector is crucial to enhancing security, resilience, and efficiency. Standards encompass rules, frameworks, guidelines, best practices, and recommendations for the development, operation, products, tools, equipment, and services. Their goal is to ensure efficient and effective production and interoperability. These standards result from the extensive knowledge, research, and experience of administrative and technical experts in the relevant field who join their efforts to suggest, discuss, and improve ideas and design a proposal for a standard for the public. Standards can be developed by various entities and organizations, both commercial and non-commercial, as well as governmental and non-governmental. The core element to build upon for the food sector is widely considered food safety, along with management and production quality standards, with food safety always constituting an integral part of food security.

For example, established in 1974, the International Organization for Standardization is a worldwide non-governmental organization of national standards bodies. The organization has designed comprehensive and structured quality management standards to advance organization efficiency and reduce failures, environmental management standards addressing environmental impacts, waste and sustainability, health and safety standards to mitigate accidents in the workplace, food safety standards to help prevent food from being contaminated and IT security standards to ensure information exchange security, among the others.

On the other hand, the CEN is an association among the National Standardization Bodies of 34 European countries. CEN's vision is that all products or services delivered within the EU follow the same rules and guidelines. It provides a platform for European Standard development and other technical documents related to various products, services, and processes. CENELEC brings technical experts from non-governmental organizations, formulating technical committees oriented to specific technology fields. The committee aims to produce standards that improve trade, enable new markets, reduce compliance costs, foster technological advancement, promote interoperability, ensure consumer health and safety, and help protect the environment.

The following reference on standards is a preliminary assessment required for exploring the food security drivers, and a more thorough analysis will be conducted within Task 8.4 (M16-M42).

This technical committee, "ISO/TC 34 – Food Products," has undertaken a broad scope of work environment relevant to food products, terminology, sampling, testing, analysis, packaging, storage, etc., aiming to cover the needs of the entire food value chain from producer to consumer. Within its broad scope, there are vital publications as well as proposals relevant to food security, such as:

3.6.1 ISO 22000:2018. Food Safety Management Systems

The ISO 22000 family of standards is a comprehensive framework focusing on food safety, emphasizing risk prevention and continuous improvement across the entire food supply chain. It involves all actors, from farmers to food service providers, and promotes transparency, traceability, and accountability. The Food Safety Management Systems (FSMS) framework includes a Plan Do Check Act (PDCA) cycle for continuous improvement incorporated into a two-level approach at both organizational and operational levels, ensuring that all processes are practical and efficient. At the organizational level, it requires the establishment of a comprehensive FSMS, a food safety management team, risk analysis, a risk management framework, and measurable objectives. Generally, top management involvement is a prerequisite to ensuring food safety is incorporated into the organization's culture and strategic planning. The operational level focuses on hazard control measures and operational processes, including hazard analysis, prerequisite programs, and HACCP principles. Risk analysis should be ongoing, documented, and revised to address identified threats and opportunities. Continuous improvement is also essential, with organizations engaging in consistent monitoring, evaluation, and action to improve processes and ensure up-to-date best practices (ISO, 2018a).

3.6.2 ISO 22006:2009. Quality Management Systems – Guidelines for Applying ISO 9001:2008 to Crop Production

It aims to assist crop producers in adopting ISO 9001:2008 to establish and manage a quality management system (QMS) for crop production processes. The framework adheres to various crops within a broad range of planting, cultivating, pesticide control, and harvesting methods and practices. The framework provides the conceptual framework of product realization, addressing the activities required to bring the product (crops) from its conceptual planning to its destination, the customer ensuring crop quality and customer satisfaction (ISO, 2009).

3.6.3 ISO/CD 20001. Food loss and waste management system — Requirements for minimizing food loss and waste across the food value chain.

Another proposed contribution relevant to Secure Food's vision is currently being drafted. The initiative aims to standardize the procedures to mitigate Food Loss and Waste (FLW) by providing a coherent framework for efficient and active FLW measurement and consistency in continuously minimizing food loss and waste. The framework is expected to specify the requirements for an organization involved in the food supply chain environments to integrate an FLW management system standard designed to include a certification mechanism for successful implementation. It will apply to all stakeholders within the food supply chain, from farmers to service providers and organizations of any size (ISO/CD 20001).

3.6.4 ISO 22301:2019. Security and Resilience – Business Continuity Management Systems – Requirements

This standard is focused on establishing, implementing, maintaining, and continuously improving a business continuity management system (BCMS). It requires extensive risk assessment and business impact analysis to maximize business protection and minimize recovery issues in potential disruptive events (ISO, 2019).

3.6.5 ISO 22320:2018. Emergency Management – Guidelines for Incident Management

This standard provides guidelines for effective incident management, focusing on establishing and improving organizations' capabilities for managing incidents and emergencies effectively, and it applies to all types and sizes of organizations. These guidelines emphasize establishing a structured incident management process focusing on assigned responsibilities and allocation of resources while also broadcasting the positive effects of cooperation strategies and joint actions (ISO, 2018b).

3.6.6 CEN TC 275. Food Analysis – Horizontal Methods

This technical committee focuses on methods of analysis to detect and determine specific properties in food nutrients or hazardous substances such as allergens, additives, biotoxins, contaminants, food supplements, and genetically modified foodstuffs.

3.6.7 CEN TC 338. Cereal and Cereal Products

This technical committee specializes in testing and characterizing cereals and cereal products, including various techniques and pending sampling methods.

3.6.8 CEN TC 446. Circularity and Recyclability of Fishing Gear and Aquaculture Equipment

This newly formed committee has developed standards for the circularity of fishing gear, aiming to establish higher quality and environmentally friendly fishing gear that is easily reused to enable the industry to achieve higher levels of sustainability.

3.6.9 CEN TC 391. Societal and Citizen Security

This technical committee aims to enhance security and resiliency by providing best practices in crisis management and disaster preparedness.

3.6.10 Codex Alimentarius Commission (CAC)

Codex Alimentarius Commission (CAC) is a joint effort of FAO and the World Health Organization (WHO), supported by 188 members and the European Union as a member organization. CAC is globally recognized as the international standardization body regarding food safety and quality, established to protect consumers' health. CAC, also known as "food law," is constituted by a collection of standards, guidelines, and good practices for the entire food value chain guiding all stages of production, all types of food at any processing level or raw ingredients, for specific hazardous or nutrient properties, and methods of sampling and analysis. Furthermore, CAC also assesses issues such as labelling, import and export inspections, and certifications.

3.6.11 Voluntary Code of Conduct for Food Loss and Waste Reduction

The Voluntary Code of Conduct, FAO, aims to outline the adoption of a framework that eliminates food loss and waste in the entire food chain, from farmer to consumer. The Voluntary Code of Conduct (CoC) is addressed to everyone involved directly or indirectly in the food system, including governments, international authorities, national and international organizations, industry corporations, households, and consumers. In its context, the CoC presents the causes of food loss and waste and provides specific guidelines and best practices for everyone involved in the food system (FAO, 2022).

3.7 Related EU and Other Projects

The global agri-food sector is at a crucial juncture where sustainability, innovation, and inclusivity are becoming non-negotiable for the future of food systems. Table 1 shows different interdisciplinary projects related to food security and the objectives of SecureFood (governance and resilience, data collection and analysis, digital tools, food supply chain, consumer preferences, healthy foods, and food waste). The projects have been grouped into crucial thematic areas: Sustainable Food Systems and Agriculture, Food Safety, Security and Policy, Digital and Technological Innovations in Food Systems, Food Waste Reduction, Nature-Based and Community Solutions, Health and Nutrition, and Partnerships and Collaborative Initiatives. These themes are instrumental in reshaping food production and consumption patterns to benefit people, the planet, and the economy. Each theme encapsulates a unique set of projects that together provide a roadmap for transforming food systems to meet the needs of current and future generations.

The "Sustainable Food Systems and Agriculture" projects aim to transform the agri-food sector towards sustainability, resilience, and innovation. These initiatives focus on multiple aspects, such as promoting short food supply chains (SFSCs) and supporting local economies, as seen in the agroBRIDGES project, which enhances connections between producers and consumers. Moreover, the BEATLES project promotes climate-smart agriculture through behavioural change, helping transition the agri-food systems towards more sustainable practices. A strong focus is placed on governance and resilience, exemplified by projects like GOLF, which integrates global and local agri-food supply chains to ensure sustainable food security. Data collection and analysis are also crucial, as demonstrated by the ENFASYS project, which assesses systemic challenges and provides pathways for sustainable farming systems. Digital tools play a significant role, especially in projects like DARWIN, which uses cutting-edge PCR-based methods and AI to enhance the transparency and safety of food supply chains. The SISTERS project leverages smart containers and bio-based packaging to reduce food waste, integrating digital solutions throughout the value chain. Consumer preferences, healthy food choices, and waste reduction are critical focus areas. The MICROORC project addresses food waste by developing technologies that extend shelf life, while the PLANEAT project co-designs interventions to promote healthier and more sustainable dietary behaviours. These initiatives focus on addressing consumer needs and reducing food waste while building a resilient, sustainable, and inclusive food system through improved governance, data use, and digital innovation. The "Food Safety, Security, and Policy" projects focus on improving traceability, rapid contamination detection, and networking among food safety stakeholders. For example, the FS4Africa project enhances food safety systems in Africa by addressing traceability and contamination issues in the informal sector, improving food security and regional trade using digital tools and policy development.

Additionally, the CATALYSE project bridges gaps between end users and innovators, providing a network for food safety actors to share knowledge and implement solutions across the value chain, thus improving resilience. Governance and resilience are also a central focus, with projects like StEPPFoS enhancing science-policy interfaces to improve policy strategies for sustainable food systems. Data collection and analysis are prioritized in projects like FNS-Cloud, which has developed a cloud solution to integrate food and nutrition security data, enabling researchers to address fragmentation in agri-food chains. Digital tools are crucial in improving food safety, as seen in the FoodSafety4EU project, which has developed a multi-stakeholder platform and risk assessment tools to enhance food safety practices across Europe. Similarly, the ZeroW project employs advanced technologies to address food waste throughout the supply chain, contributing to a sustainable food system by reducing resource use and greenhouse gas emissions. Food supply chain innovations are evident in the CO-FRESH project, which implements technological and non-technological innovations to create environmentally sustainable and socio-economically balanced agri-food value chains. Moreover, the SHEALTHY project addresses consumer preferences for healthy foods by employing non-thermal methods to preserve the nutritional quality and shelf life of minimally processed fruits and vegetables. These projects collectively aim to create a resilient, sustainable, and inclusive food system that enhances governance, employs advanced data and digital tools, improves supply chain efficiency, and ensures consumer access to healthy, safe, and affordable food, all while addressing the challenges of climate change and food security.

The "Digital and Technological Innovations in Food Systems" project focuses on transforming food systems through digital and technological advancements to promote sustainability, transparency, and health. For example, DigitAF provides digital tools to support adopting agroforestry systems, helping farmers optimize their agronomic, economic, and environmental performance. This project also supports policymakers by offering data-driven insights to design more effective biodiversity and climate change mitigation policies. The DRG4FOOD project is another critical initiative to build a responsible, data-driven food system. It aims to enhance transparency and trust in food safety, security, and sustainability through a roadmap that integrates digital responsibility goals, including openness, sovereignty, and fairness in using data for food tracking and targeted nutrition. TrustEat employs blockchain technology regarding supply chain transparency to increase reliability and traceability across the food value chain. At the same time, TITAN uses AI, IoT, and DNA-based rapid detection methods to enhance food safety and authenticity. Projects like OpenAgri empower farmers and consumers by democratizing digital farming through open-source software, enabling farmers to co-create cost-effective, energy-efficient digital tools for agriculture. This helps address issues like weak connectivity and data-sharing concerns, particularly in remote areas. Meanwhile, FoodSHIFT2030 focuses on scaling citizen-led food innovations in local communities, promoting circular economy principles and sustainable design to empower citizens to shape food systems.

The "Food Waste Reduction" projects aim to tackle food loss and waste through innovative and multidisciplinary approaches across the food value chain. These projects focus on developing solutions such as dynamic pricing systems, technological tools, and reforms to marketing standards to prevent waste and create economic value from previously discarded resources. For instance, the BREADCRUMB project investigates the impacts of food marketing standards on waste generation and explores ways to improve market access for suboptimal foods, helping businesses and consumers reduce waste while generating business value. Similarly, the ROSETTA project conducts pilot experiments across the EU to test alternative market access for suboptimal foods, reducing food waste by up to 80% and offering policy recommendations to reform marketing standards. Data collection and analysis are central to projects like WASTELESS, which develops tools to measure and monitor food losses and waste, providing decision-support tools for stakeholders to reduce waste and reuse resources efficiently across the supply chain. The LOWINFOOD project also deploys technological, social, and organizational innovations to reduce waste in perishable food value chains such as fruits, vegetables, bakery products, and fish. Digital tools are integral to these efforts, as seen in the FRIENDS Reduce Food Waste project, which uses dynamic pricing technology to reduce waste by over 40%, ensuring a smoother supply chain and providing fairer prices to consumers.

Additionally, projects like R3PACK explore sustainable packaging solutions by leveraging advanced technologies to reduce plastic use, rethinking packaging strategies, and ensuring food safety in reusable packaging. These projects prioritize multi-stakeholder collaboration to prevent food waste, improve resource efficiency, and address environmental challenges, building sustainable, circular food systems that reduce waste and create economic value from surplus resources. The "Nature-based and Community Solutions" projects focus on promoting sustainability, biodiversity, and climate resilience through collaborative approaches. These initiatives work to tackle food security, urban sustainability, and environmental challenges by involving local communities, policymakers, and stakeholders in co-designing solutions. For instance, COEVOLVERS explores governance models for nature-based solutions by involving vulnerable groups and non-humans, aiming to co-create governance techniques that enhance resilience and inclusivity within urban green spaces. Another project, FUSILLI, establishes 12 Living Labs in different cities, integrating food systems into urban transformation to address nutrition, sustainability, and food security by improving actions across the food value chain. Data collection and analysis are critical components of projects like CULTIVATE, which develops the Food Sharing Compass to monitor and map food-sharing initiatives, supporting local communities in reducing food waste and enhancing resilience.

Similarly, the Food Trails project uses Living Labs to test and co-implement food system actions in European cities, aligning with the EU's Farm to Fork strategy and FOOD2030 policy to promote healthier and more inclusive food environments. These projects also leverage digital tools to support food security and sustainability. For example, ECO-READY implements a real-time surveillance system to track climate and biodiversity changes, empowering communities and policymakers to respond to environmental challenges. Robin Food revalorizes surplus food in the supply chain, transforming it into products distributed to socially vulnerable groups, thus contributing to sustainability and food accessibility.

The "Health and Nutrition" projects aim to address challenges in sustainable food production, healthy diets, and food security through innovative approaches. For example, DOMINO explores the health benefits of fermented foods, investigating how plant-based fermented foods can improve gut health and sustainability. Similarly, HealthFerm focuses on developing new, nutritious fermented products based on pulses and cereals while researching their impact on human health. Projects like LIKE-A-PRO and Smart Protein aim to promote alternative proteins by developing innovative, sustainable protein products. Smart Protein, for instance, utilizes crops such as lentils and quinoa alongside food waste streams to produce plant-based meat, dairy, and bakery alternatives. By addressing food waste and social inclusion, FOOD4INCLUSION works to improve access to healthy diets for disadvantaged groups by promoting food literacy and reducing food waste.

Meanwhile, FOODGUARD focuses on extending food shelf life and minimizing food waste through microbiome innovations and smart packaging. Personalized nutrition is another key focus, as seen in the PROTEIN and CoDiet projects. PROTEIN uses data-driven tools to offer personalized nutrition plans tailored to individual needs, while CoDiet employs AI to analyse dietary impacts on health, creating personalized nutritional advice.

The "Partnerships and Collaborative Initiatives" projects aim to address global challenges through innovative, sustainable, and community-driven approaches, focusing on improving food systems and fostering cross-sectoral collaboration. For example, the NESTLER project promotes a One-Health partnership between the EU and Africa by integrating advanced digital tools such as satellite data and IoT devices to monitor the well-being of animals, plants, and humans. It also explores sustainable protein sources like insect farming to support circular economies and improve food security. Governance and resilience play a central role in these initiatives, as seen in the FOSTER project, which aims to build a new governance structure for knowledge and innovation systems in Europe's food systems. This project fosters collaboration between citizens, academia, and policymakers to ensure sustainable food system outcomes. Data collection and analysis are essential in projects like FEAST, which maps dietary patterns and factors shaping food environments. Through co-creation and tech-based solutions, it helps develop tools to empower individuals and policymakers to promote healthier and more sustainable nutritional behaviours. Concerning digital tools, the EIT Food Protein Diversification Think Tank explores innovative solutions for protein diversification, using data-driven insights to meet global challenges in food systems. It also addresses consumer trust, aiming to ensure new protein sources are safe and environmentally sustainable. Food supply chains are strengthened through initiatives like Strengthening Agri-Food Value Chains, which seeks to improve the integration of small and medium-sized agri-food producers and promote sustainable practices in Morocco, aligning with green and resilient futures. The projects also emphasize consumer preferences and making healthy diets accessible. The Food4Inclusion project tackles food insecurity by ensuring disadvantaged groups across Europe can access quality, affordable food while advocating for inclusive food systems through policy change.

Table 1 – List of related EU-funded projects.

Acronym	Title	Grant Agreement ID	Governance and Resilience	Data Collection and Analysis	Digital Tools	Food Supply Chain	Consumer preferences, healthy foods, and food waste	Website
Sustainable Food Systems and Agriculture								
agroBRIDGES	Building sustainable food systems for farmers and consumers	101000788			√	√		https://www.agrobridges.eu/
BEATLES	Behavioural Change Towards Climate-Smart Agriculture	101060645					√	https://beatles-project.eu/
ENFASYS	Sustainable Farming Systems	101059589	√	√			√	https://www.enfasysproject.eu/
GOLF	Integration of Global and Local Agri-Food Supply Chains towards Sustainable Food Security	777742	√	√		√		https://www.liverpool.ac.uk/management/research/centres/cscr/golf/
FOODPathS	Paving the way of the European Partnership for Sustainable Food Systems	101059497	√				√	https://www.foodpaths.eu/
ShapingBio	Shaping the bioeconomy of the future	101060252	√				√	https://www.shapingbio.eu/
SISTERS	Systemic Innovation for a SusTainable reduction of the EuRopean food waStage	101037796		√	√	√		https://sistersproject.eu/
FEASTS	Fostering European cellular Agriculture for Sustainable Transition Solutions	101136749					√	https://cordis.europa.eu/project/id/101136749
DARWIN	Transition to safe, sustainable food systems through new and innovative detection methods and digital solutions for plant-based products derived from new genomic techniques under a co-creation approach	101136462	√	√	√			https://cordis.europa.eu/project/id/101136462
INNOECOFOOD	Eco-innovative technologies for improved nutrition, sustainable production, and marketing of agroecological food products in Africa	101136739	√	√	√	√	√	https://cordis.europa.eu/project/id/101136739

Acronym	Title	Grant Agreement ID	Governance and Resilience	Data Collection and Analysis	Digital Tools	Food Supply Chain	Consumer preferences, healthy foods, and food waste	Website
PIMENTO	Promoting Innovation of ferMENTed fOods	MoU – 068/21					√	https://fermentedfoods.eu/
MICROORC	Orchestration of food system microbiomes to minimize food waste	101136248				√	√	https://cordis.europa.eu/project/id/101136248
CEA-FIRST	Consortium Europe-Africa for Research and Innovation on Food Systems Transformation	101136771	√	√				https://cordis.europa.eu/project/id/101136771
UP-RISE	EU-AU Partnership for Resilient, Inclusive Safe Food Systems for Everyone	101136649	√	√				https://cordis.europa.eu/project/id/101136649
EdiCitNet	Edible Cities Network	776665	√		√		√	https://www.edicitnet.com/
GrapeBreed4IPM	Developing sustainable solutions for viticulture through multi-actor innovation targeting breeding for integrated pest management	101132223	√	√		√		https://cordis.europa.eu/project/id/101132223
RegenAg Revolution	Regenerative Agriculture – mentoring farmers for the benefit of all	Funded by EIT Food	√			√		https://www.eitfood.eu/projects/regenag-revolution?_gl=1*evhzq3*_up*MQ..&gclid=CjwKCAjwrcKxBhBMEiwAIVF8rCqXDf58_zOZx9akx2jXrXnf8vrzh87bLTT3TZizWZ5tr1mQhylYqxoCHvAQAvD_BwE
GenB	Generation Bioeconomy	101060501			√		√	https://www.genb-project.eu/
Nutri2Cycle	Transition towards a more carbon and nutrient efficient agriculture in Europe	773682	√	√				https://www.nutri2cycle.eu
OrganicYieldsUP	Improving yields in organic cropping systems	101137068	√	√				https://cordis.europa.eu/project/id/101137068

Acronym	Title	Grant Agreement ID	Governance and Resilience	Data Collection and Analysis	Digital Tools	Food Supply Chain	Consumer preferences, healthy foods, and food waste	Website
STEP UP	Sustainable Livestock Systems Transition and Evidence Platform for Upgrading Policies	101136785		√		√		https://cordis.europa.eu/project/id/101136785
SUSINCHAIN	SUStainable INsect CHAIN	861976	√	√		√		https://susinchain.eu
SMART PROTEIN	Smart Protein for a Changing World.	862957		√		√	√	https://smartproteinproject.eu
SolACE	Solutions for improving Agroecosystem and Crop Efficiency for water and nutrient use	727247	√				√	https://www.solace-eu.net/index.html
Legumes Translated	Translating knowledge for legume-based farming for feed and food systems.	817634	√					https://www.legumestranslated.eu/project-partners
PLAN'EAT	On our Way to Transforming Food Systems	101061023	√				√	https://planeat-project.eu/
COREnet	Connecting advisors towards a European Network for consumer-producer chains	101060905	√	√		√		https://shortfoodchain.eu/
VISIONARY	Food Provision through Sustainable Farming Systems and Value Chains	101060538	√			√	√	https://visionary-project.eu/
Food Safety, Security, and Policy								
FS4Africa	The Food Safety for Africa	101136916	√		√	√		https://cordis.europa.eu/project/id/101136916
CATALYSE	Catalysing scientific innovation into food safety action	101136754	√	√	√			https://cordis.europa.eu/project/id/101136754
FNS CLOUD	Food Nutrition Security Cloud	863059		√	√		√	https://www.fns-cloud.eu/
ZeroW	Systemic innovations for zero food waste	101036388				√	√	https://www.zerow-project.eu/
FOLOU	Bringing knowledge and consensus to prevent and reduce Food Loss at the primary production stage	101084106	√			√	√	https://www.folou.eu/

Acronym	Title	Grant Agreement ID	Governance and Resilience	Data Collection and Analysis	Digital Tools	Food Supply Chain	Consumer preferences, healthy foods, and food waste	Website
LESTRA	Transactional investigations of learning in view of sustainability transitions	949485		√		√		https://www.cdo.ugent.be/project/transactional-investigations-learning-view-sustainability-transitions-lestra
StEPPFoS	Strengthening Evidence-Based Policy Practice for Sustainable Food Systems under the EU-AU Partnership	101136770	√	√				https://cordis.europa.eu/project/id/101136770
CO-FRESH	The European Project CO-FRESH	101000852			√	√		https://co-fresh.eu/
FoodCLIC	The acronym FoodCLIC stands for 'integrated urban FOOD policies – developing sustainability Co-benefits, spatial Linkages, social Inclusion and sectoral Connections to transform food systems in city-regions		√			√	√	https://foodclic.eu/
BIOVALUE	Fork-to-farm agent-based simulation tool augmenting BIOdiversity in the agri-food VALUE chain	101000499		√	√			https://www.biovalue-project.eu
FOSC	Food System and Climate (FOSC)	862555	√	√				https://cordis.europa.eu/project/id/862555
FoodSafety4EU	Food Safety System of the Future	101000613	√		√			https://foodsafety4.eu/
SHEALTHY	Non-Thermal physical technologies to preserve healthiness of fresh and minimally processed fruit and vegetables	817936				√	√	https://www.shealthy.eu
Future Food Makers	FutureFoodMakers: shaping the food sector we all need	818182	√				√	https://www.eitfood.eu/projects/become-a-futurefoodmaker?_gl=1*6bt57m*_up*MQ..&gclid=CjwKCAjwrcKxBhBMEiwAIVF8rCqXDf58_zOZx9akx2jXrXnf

Acronym	Title	Grant Agreement ID	Governance and Resilience	Data Collection and Analysis	Digital Tools	Food Supply Chain	Consumer preferences, healthy foods, and food waste	Website
								8vrzh87bLTT3TZizWZ5tr1mQhylYqxoCHvAQAvD_BwE
MATS	Making Agricultural Trade Sustainable	101000751	√			√		https://sustainable-agri-trade.eu
EThichain	Authenticity of food with ethic and religious perspective: increasing trust in European supply system	101000652		√	√	√	√	https://www.eitfood.eu/projects/authenticity-of-food-with-ethic-and-religious-perspective-increasing-trust-in-european-supply-system?_gl=1*1vpz1zv*_up*MQ..&gclid=CjwKCAjwrcKxBhBMEiwAIVF8rCqXDf58_zOZx9akx2jXrXnf8vrzh87bLTT3TZizWZ5tr1mQhylYqxoCHvAQAvD_BwE
RURALITIES	Climate smart, ecosystem-enhancing and knowledge-based rural expertise and training centres	101060876	√	√	√			https://www.ruralities-project.eu/
Digital and Technological Innovations in Food Systems								
DigitAF	DIGItal Tools to boost AgroForestry	101059794	√	√	√			https://digitaf.eu/
DRG4FOOD	Digital Responsibility Goals in Food	101086523		√	√		√	https://drg4food.eu/
TrustEat	Building a Trusty Future Food System by using Blockchain Tech	952600		√	√	√		https://www.trusteat.eu/
OpenAgri	Democratising digital farming through tailored open source and open hardware solutions	101134083		√	√			https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/how-to-participate/org-details/999999999/pr

Acronym	Title	Grant Agreement ID	Governance and Resilience	Data Collection and Analysis	Digital Tools	Food Supply Chain	Consumer preferences, healthy foods, and food waste	Website
								oject/101134083/program/43108390/details
TITAN	Transparency solutions for transforming the food system	101059794	√	√	√	√		https://titanproject.eu/
FOX	Food processing in a Box	817683				√	√	https://www.fox-foodprocessinginabox.eu/about-fox/
TRUSTyFOOD	Providing future scenarios and a roadmap for a wide agri-food blockchain implementation	952600		√	√	√		https://www.trustyfood.eu/
AGRICORE	Agent-based support tool for the development of agriculture policies	101134083	√	√	√			https://agricore-project.eu
FAIRCHAIN	Innovative technological, organisational and social solutions for FAIRer dairy, fruit and vegetable value CHAINs	10106073	√	√	√			https://www.fairchain-h2020.eu/
Stance4Health	Smart Technologies for personAlised Nutrition and Consumer Engagement	817683		√	√		√	https://www.stance4health.com
REIMS	REIMS-based analysis platform for improved traceability and consumer purchase intention of high-end food products	-		√		√	√	https://www.eitfood.eu/projects/reims-based-analysis-platform-for-improved-traceability-and-consumer-purchase-intention-of-high-end-food-products-2020?_gl=1*1buzbq2*_up*MQ..&gclid=CjwKCAjwrcKxBhBMEiwAIVF8rCqXDf58_zOZx9akx2jXrXnf8vrzh87bLTT3TZizWZ5tr1mQhylYqxoCHvAQAvD_BwE

Acronym	Title	Grant Agreement ID	Governance and Resilience	Data Collection and Analysis	Digital Tools	Food Supply Chain	Consumer preferences, healthy foods, and food waste	Website
RESPIN	REinforce Science-Policy interfaces in innovative ways to boost effectiveness and INterconnectedness of biodiversity and climate policies	816078	√					https://cordis.europa.eu/project/id/101135490
CODECS	COoperative ITS DEployment Coordination Support	101000723	√	√	√			https://www.horizoncodecs.eu/
COMFOCUS	Exploring Food Consumer Science on a European scale	816303		√			√	https://cordis.europa.eu/project/id/101005259
Data4Food2030	Pathways towards a fair, inclusive and innovative Data Economy for Sustainable Food Systems	101059473	√	√	√			https://data4food2030.eu/
FOODITY	FOod and nutritiOn Data-driven innovation respectful of citizen's Data SovereIgnTY	101135490	√					https://foodity.eu/
FoodSHIFT2030		10041831	√	√			√	https://foodshift2030.eu/
Food Waste Reduction								
BREADCRUMB	BRinging Evidence-bAseD food Chain solutions to prevent and RedUce food waste related to Marketing standards, and deliver climate and circularity co-Benefits	101136701	√	V		√	V	https://cordis.europa.eu/project/id/101136701
ROSETTA	Reducing food waste due to marketing standards through alternative market access	101136427	√	V		√	V	https://cordis.europa.eu/project/id/101136427
WASTELESS	Waste Quantification Solutions to Limit Environmental Stress	101084222	√	√	√	√	√	https://wastelesseu.com/
FOODRUS	An Innovative Collaborative Circular Food System to Reduce Food Waste and Losses in the Agri-food Chain	Grant agreement ID: 101000617	√	√	√	√	√	https://www.foodrus.eu
From Leaf to Root	From Leaf to Root – Holistic Use of Vegetables		√				√	https://www.eitfood.eu/projects/from-leaf-to-root-holistic-use-of-vegetables-

Acronym	Title	Grant Agreement ID	Governance and Resilience	Data Collection and Analysis	Digital Tools	Food Supply Chain	Consumer preferences, healthy foods, and food waste	Website
								2020?_gl=1*kmlg7y*_up*MQ..&gclid=CjwKCAjwrcKxBhBMEiwAIVF8rCqXDf58_zOZx9akx2jXrXnf8vrzh87bLTT3TZizWZ5tr1mQhylYqxoCHvAQAvD_BwE
FRIENDS Reduce Food Waste	FRIENDS Reduce Food Waste		√		√	√	√	https://www.eitfood.eu/projects/friends-reduce-food-waste?_gl=1*qw849p*_up*MQ..&gclid=CjwKCAjwrcKxBhBMEiwAIVF8rCqXDf58_zOZx9akx2jXrXnf8vrzh87bLTT3TZizWZ5tr1mQhylYqxoCHvAQAvD_BwE
LOWINFOOD	Multi-actor design of low-waste food value chains through the demonstration of innovative solutions to reduce food loss and waste	101000439	√	√		√	√	https://lowinfood.eu/
R3PACK	Reduce, Reuse, Rethink PACKaging: towards novel fiber-based packaging and reuse schemes uptake	101060806	√					https://www.r3pack.eu
OPTAIN	OPtimal strategies to retAIN and re-use water and nutrients in small agricultural catchments across different soil-climatic regions in Europe	862756	√	√				https://www.optain.eu
LOWINFOOD	Multi-actor design of low-waste food value chains through the demonstration of innovative solutions to reduce food loss and waste	101000439	√	√		√	√	https://lowinfood.eu
R3PACK	Reduce, Reuse, Rethink PACKaging: towards novel fiber-based packaging and reuse schemes uptake	I101060806	√			√		https://cordis.europa.eu/project/id/101060806

Acronym	Title	Grant Agreement ID	Governance and Resilience	Data Collection and Analysis	Digital Tools	Food Supply Chain	Consumer preferences, healthy foods, and food waste	Website
CHORIZO	Changing practices and Habits through Open, Responsible, and social Innovation towards Zer0 food waste	101060014	√	√	√	√	√	https://chorizoproject.eu/
ENOUGH	European food chain supply to reduce GHG emissions by 2050	101036588	√			√		https://enough-emissions.eu/
Hungry EcoCities	Hungry EcoCities investigates a more sustainable and responsible agri-food system	101069990	√		√		√	https://starts.eu/hungryecocities/
Nature-based and Community Solutions								
COEVOLVERS	Coevolutionary approach to unlock the transformative potential of nature-based solutions for more inclusive and resilient communities	101084220	√					https://co-evolvers.eu/
RESPONSE	RESPONSE - to society and policy needs through plant, food and energy sciences	847585	√					https://www.plantsciences.uzh.ch/en/research/fellowships/response.html
FUSILLI	Fostering the urban Food system transformation though innovative living labs implementation	101000717	√			√	√	https://fusilli-project.eu/
URBAG	Integrated System Analysis of Urban Vegetation and Agriculture	818002	√	√				https://urbag.eu/
CULTIVATE	The Food Sharing Compass-An Online Platform for Multiple Stakeholders to Support Sustainable and Resilient Food Sharing	101083377	√		√	√	√	https://cultivate-project.eu/
GeneBEcon	Capturing the potential of Gene editing for a sustainable BioEconomy	101061015	√			√		https://genebecon.eu/about/
ECO-READY	Achieving Ecological Resilient Dynamism for the European food system through consumer-driven policies, socio-ecological challenges, biodiversity, data-driven policy, sustainable futures	101084201	√	√	√			https://www.eco-ready.eu/

Acronym	Title	Grant Agreement ID	Governance and Resilience	Data Collection and Analysis	Digital Tools	Food Supply Chain	Consumer preferences, healthy foods, and food waste	Website
Food Trails	Building pathways towards FOOD 2030-led urban food policies	101000812	√			√	√	https://foodtrails.milanurbanfoodpolicypact.org/
Health and Nutrition								
DOMINO	Harnessing the Potential of Fermentation for Healthy and Sustainable Foods	101060218		√			√	https://www.domino-euproject.eu/
FOODGUARD	Microbiome applications and technological hubs as solutions to minimize food loss and waste	101136542		√	√		√	https://cordis.europa.eu/project/id/101136542
FLORA	Sustainable and healthy food solutions: system dynamics and trade-offs	Funded by a Starting Grant from the European Research Council	√			√	√	https://www.geosciences.ens.fr/en/flora
CUES	Consumers' Understanding of Eating Sustainably	101136507	√				√	https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/how-to-participate/org-details/999999999/project/101136507/program/43108390/details
CIRCALGAE	The EU-funded Horizon Europe project CIRCALGAE aims to develop sustainable algae-based biorefineries and products supporting the health of aquatic ecosystems for a healthy planet and people	101060607				√		https://www.safefoodadvocacy.eu/projects/circalgae/
EFFECT	Environmental public goods From Farming through Effective Contract Targeting	817903	√					https://project-effect.eu

Acronym	Title	Grant Agreement ID	Governance and Resilience	Data Collection and Analysis	Digital Tools	Food Supply Chain	Consumer preferences, healthy foods, and food waste	Website
Nati0Ons	National engagement activities to support the launch of the Mission 'A Soil Deal for Europe' 100 Living Labs and Lighthouses	101090738	√					https://www.eitfood.eu/projects/nati0Ons-supporting-the-eu-mission-a-soil-deal-for-europe-across-national-communities?_gl=1*3ydt4o*_up*MQ..&gclid=CjwKCAjwrcKxBhBME
FOOD4INCLUSION	Unhealthy diets considered a primary factor of overweight and obesity and noncommunicable diseases occurrence	-					√	https://www.safefoodadvocacy.eu/projects/undergraduate-module-in-nutrition/
PROTEIN	PeRsOnalized nutriTion for hEalthy livINg	817732		√	√		√	https://protein-h2020.eu
HealthyLivestock	Tackling Antimicrobial Resistance through improved livestock Health and Welfare	773436	√	√		√		https://healthylivestock.net
Preventia	NCDs prevention and health promotion through training, networking and awareness-raising across the EU – EUPr3ventNCDs	-					√	https://www.safefoodadvocacy.eu/projects/preventia/
LIKE-A-PRO	LIKE-A-PRO	101083961				√	√	https://www.safefoodadvocacy.eu/projects/like-a-pro/
Improving juiciness of plant-based meat alternatives	Making meat substitutes more palatable	-				√	√	https://www.eitfood.eu/projects/improving-juiciness-of-plant-based-meat-alternatives?_gl=1*1lns3ug*_up*MQ..&gclid=CjwKCAjwrcKxBhBME

Acronym	Title	Grant Agreement ID	Governance and Resilience	Data Collection and Analysis	Digital Tools	Food Supply Chain	Consumer preferences, healthy foods, and food waste	Website
HealthFerm	Innovative pulse and cereal-based food fermentations for human health and sustainable diets	**101060247**		√			√	https://www.healthferm.eu/
CoDiet	Combating Diet Related Non-Communicable Disease through Enhanced Surveillance	**101084642**		√			√	https://www.codiet.eu/
Partnerships and Collaborative Initiatives								
NESTLER	oNe hEalth SusTainabiLity partnership between EU-AFRICA for food sEcuRity	**101060762**	√	√	√			https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/how-to-participate/org-details/999999999/project/101060762/program/43108390/details
FEAST	Food systems that support transitions to hEalthy And Sustainable dieTs	**101060536**	√	√			√	https://feast2030.eu/
Increasing consumer trust and support for the food supply chain and for food companies	Co-creating initiatives to increase consumer trust in food	-				√	√	https://www.eitfood.eu/projects/increasing-consumer-trust-and-support-for-the-food-supply-chain-and-for-food-companies-2020
GROW	GROW: Empowering Farmers for a Sustainable Journey	-	√		√	√		https://www.eitfood.eu/projects/grow?_gl=1*1qkl212*_up*MQ..&gclid=CjwKCAjwrcKxBhBME

Acronym	Title	Grant Agreement ID	Governance and Resilience	Data Collection and Analysis	Digital Tools	Food Supply Chain	Consumer preferences, healthy foods, and food waste	Website
BrightSpace	Increasing the contribution of EU agriculture to climate change action	**101060075**	√			√		https://iiasa.ac.at/news/oct-2023/increasing-contribution-of-eu-agriculture-to-climate-change-action
Strengthening Agri-Food Value Chains	Strengthening Agri-Food Value Chains	**P158346**	√			√		https://projects.worldbank.org/en/projects-operations/project-detail/P158346
FOSTER	Fostering food system transformation by integrating heterogeneous perspectives in knowledge and innovation within the ERA	**101059954**	√				√	https://fosterfoodsystem.eu/
FOOD4INCLUSION	FOOD4INCLUSION	**-**					√	https://www.safefoodadvocacy.eu/projects/food4inclusion/
SchoolFood4Change	SchoolFood4Change	**101036763**	√			√	√	https://schoolfood4change.eu/

4 Food Security Drivers

4.1 SecureFood's Conceptual Framework

The conceptual framework for food security drivers in SecureFood builds on the four pillars of food security as defined by FAO (2006) – Availability, Access, Utilization, and Stability – while also integrating the updated approach from the EC (2023) that includes two additional pillars: Agency and Sustainability.

The four pillars of food security, as defined by the FAO (2006), are:

- **Availability:** This refers to the physical presence of enough food produced and available in the market for people to meet their needs. It involves food production, distribution, and trade. If food is available in a country or region but not accessible to individuals, food security is not achieved.
- **Access:** It refers to individuals' and households' ability to obtain food through their own production or purchasing power in markets. This can depend on income, food prices, market systems, and distribution networks. Economic access (ability to afford food) and physical access (proximity to food markets) are crucial, particularly for vulnerable populations.
- **Utilization:** This pillar is about how food is used and absorbed by the body. It includes the nutritional value of food, food preparation, and cultural practices. Safe and nutritious food ensures that people's dietary needs are met for a healthy and active life.
- **Stability:** It emphasizes that food must be available, accessible, and well-utilized consistently over time. Stability addresses risks such as economic, climatic, or political disruptions that threaten food supply or access, ensuring that food security is sustained over the long term.

In the Commission Staff Working Document "Drivers of Food Security" (EC, 2023d), two additional pillars were introduced to reflect the evolving complexity of food systems and the interdependence among actors, processes, and external factors that influence food security:

- **Agency:** It refers to the capacity of the food system's actors to make their own decisions about food. For example, it can depend on the supply chain's operations and how food is distributed from "farm to fork." Unrestrained food transport offers food actors the necessary variety of food products covering dietary needs.
- **Sustainability:** It is the long-term ability of food systems to provide food security in a way that does not compromise the economic, social, and environmental bases that generate food security for future generations.

Likewise, food security drivers within this document are grouped into 7 main risk types, namely (i) Biophysical and Environmental, (ii) Technology and Innovation, (iii) Economic and Market, (iv) Food Value Chain, (v) Political & Institutional, (vi) Socio-cultural, (vii) and Demographic Drivers (see Figure 2).

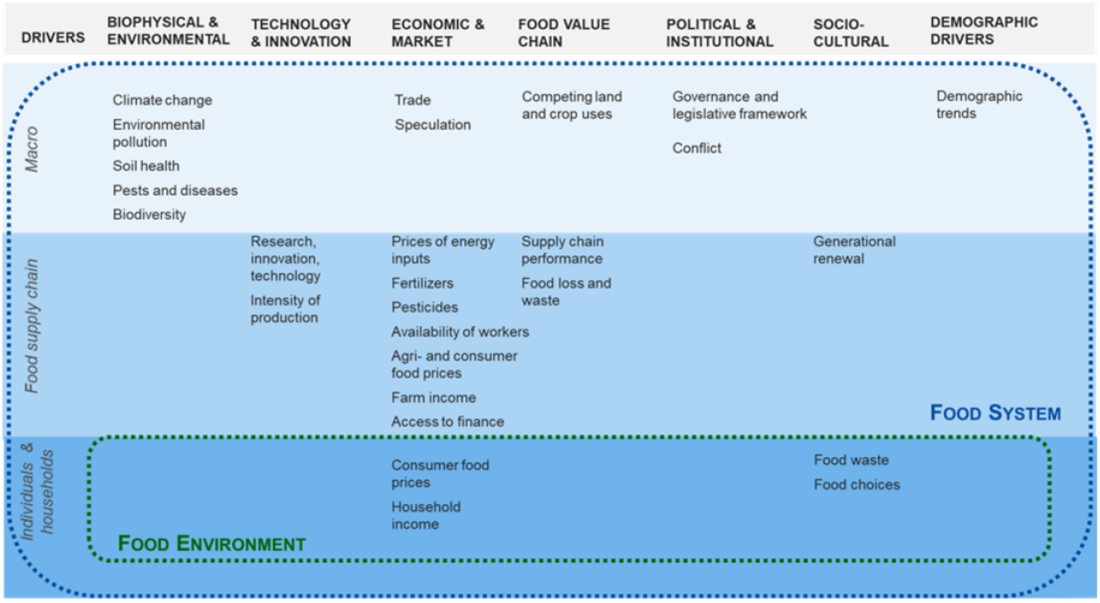

*Figure 2 – Conceptual framework for analysing drivers affecting food security in the EU as discussed in the Staff **Working Document**[2].*

In a more recent study published by the JRC (Bertolozzi-Caredio et al., 2023), six risk types were identified (Figure 3), reflecting to a large extent the drivers published by the EC (2023) with a modification of merging of Socio-Cultural and Demographic Drivers into "Socio-cultural and Demographic" risk type. This consolidation shows that socio-cultural and demographic factors are closely intertwined in shaping food systems. Socio-cultural dynamics, such as dietary preferences, intersect with demographic shifts like urbanization, migration, and population growth. Together, these factors influence food demand, production, and market trends.

[2] Adapted by the EC (2023).

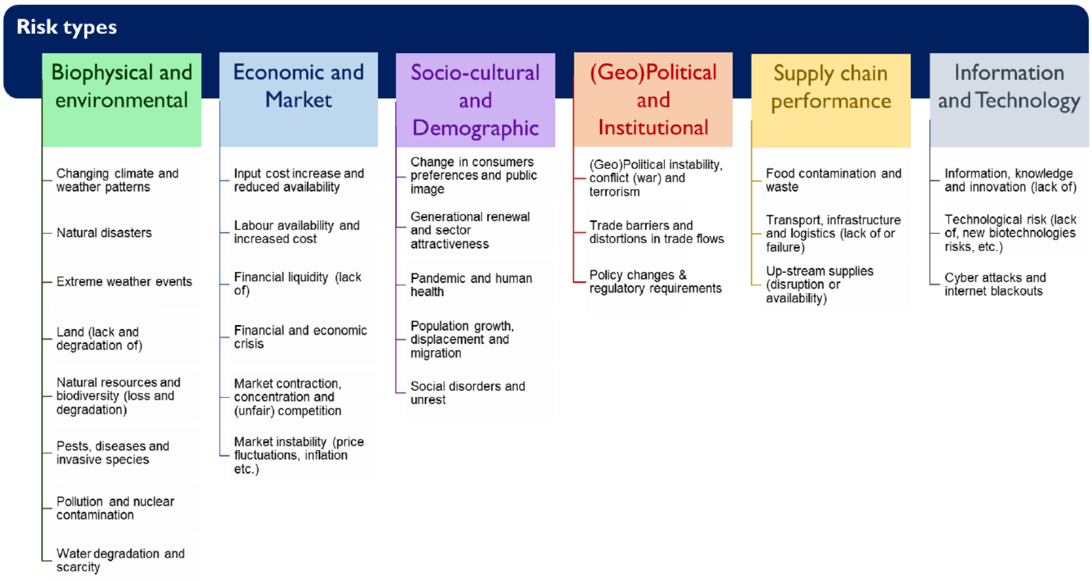

Figure 3 – Categorization of the identified risk types[3].

The SecureFood conceptual framework addresses the complex landscape of food security drivers using an integrated, system-thinking approach. It combines a flexible approach to drivers, enabling a nuanced analysis of food security and recognizing that targeted interventions can shift the balance between positive and negative drivers, turning potential threats into opportunities to strengthen food systems. For example, introducing climate-resilient crops can mitigate the negative impact of drought, while the absence of infrastructure development or political instability can weaken food systems. By consolidating key categories and organizing drivers into a structured hierarchy, the framework remains manageable and comprehensive, allowing for precise analysis and effective policy responses without losing the granularity necessary for targeted interventions based on measurable aspects of each driver.

Building on the six pillars of food security, the framework adapts and introduces new elements to manage the large number of drivers identified in the literature (over 100). To streamline these, SecureFood organizes drivers into three levels: main categories, 1st level subcategories, and 2nd level subcategories. The 2nd level subcategories represent specific variables influencing food security, allowing for a detailed analysis of how different factors impact outcomes (Table 2). More specifically, the main characteristics of the framework include:

- **The main categories of drivers** are broad, encompassing categories that group drivers based on their overarching impact on food systems. Compared to the 6 risk types of the Bertolozzi-Caredio et al. (2023) study, the **SecureFood** conceptual framework includes 5 main categories of drivers (Biophysical and Environmental; Technology, Innovation, and Supply Chain; Market and Economic; Political and Institutional; Socio-cultural and Demographic), merging food supply chain with technology and innovation in one category. This merger was conducted to reflect the transformative role of technological advancements and digital tools in modernizing food systems. Integrating technology and innovation with the food supply chain emphasizes how research and digital advancements can enhance supply chain efficiency, transparency, and resilience. To support this,

[3] Adapted by the Bertolozzi-Caredio et al. (2023).

SecureFood will develop and apply several digital tools, such as digital twins, early warning systems, and an information exchange platform, WASTE-SEC.

- **Subcategories of drivers** provide a more detailed view of specific drivers within each main category. The 2nd level subcategories, which represent vital variables, allow for a finer-grained analysis of how individual factors impact food security. For instance, under biophysical and environmental drivers, a 1st level subcategory includes changing climate and weather patterns. In contrast, the 2nd level subcategory refers to specific variables such as temperature or precipitation changes and natural disasters directly impacting food security outcomes.
- Each variable (e.g., liquidity, market price volatility, contraction, concentration, unfair competition, and education and awareness) can be further broken down into **variants**, representing different potential outcomes that may be positive, neutral, or negative depending on the specific conditions. For instance, the variable of liquidity may have multiple outcomes such as *positive*: businesses may have sufficient financial resources and easy access to credit, ensuring investment in new technologies and expansion; *neutral*: limited access to credit could create occasional liquidity issues, requiring careful financial planning and limiting growth opportunities; or *negative*: severe liquidity problems could result in underinvestment in technology and reduced operational capacity. Regarding market price volatility, stable prices across the supply chain can create predictability and steady profits (*positive*); prices may fluctuate periodically but remain manageable through adaptive strategies (*neutral*); or significant price volatility driven by external shocks could disrupt business planning and revenues (*negative*). In the case of contraction, concentration, and unfair competition, a competitive market environment might allow smaller players to thrive under fair regulations (*positive*); increasing market concentration may create some monopolistic behavior but still allow niche opportunities for smaller players (*neutral*); or high market concentration could lead to monopolistic practices that stifle competition and innovation (*neutral*). For education and awareness, significant improvements in public initiatives could result in widespread consumer awareness of sustainable food practices, driving positive behavior changes (*positive*); moderate enhancements may lead to intermittent changes in consumer choices, with remaining knowledge gaps (*neutral*); or education programs might be ineffective, leading to minimal consumer understanding and perpetuating unsustainable consumption patterns (*negative*). These variants will be further explored in other Work Packages (WPs) of the SecureFood project to assess their full impact on food security. While the framework identifies these key variables, the detailed examination of their variants (how target variables may behave under various scenarios) will be addressed in **Task 3.1 (Foresight analysis)** of the SecureFood project. This further exploration will provide a more comprehensive understanding of how these variants can affect food security, allowing for more targeted interventions and adaptive strategies to improve the resilience of food systems.
- **Positive/negative drivers:** Another distinctive feature of the **SecureFood** framework is its dynamic approach to understanding the impact of drivers. Drivers are not inherently positive or negative. Instead, their effects on food security depend on their presence or absence. Positive drivers are factors that strengthen food security when present. For example, introducing advanced agricultural technologies, policy reforms to improve market access, or innovations in sustainable farming practices are considered positive drivers for enhancing food system resilience, availability, and access. Negative drivers emerge when positive drivers are absent or when **threats** are present. For instance, the lack of infrastructure development, climate resilience measures, or political instability can weaken food systems and reduce food security. Natural disasters, conflict, and trade disruptions

are also considered negative drivers that can severely impact food availability, access, and stability.

4.2 Identified Drivers

Table 2 presents the identified drivers based on the two studies (EC, 2023c; Bertolozzi-Caredio et al., 2023) together with other ones found in the literature, as well as the feedback received by SecureFood stakeholders and the developed EU Survey. The table is a critical tool for stakeholders aiming to prioritize interventions and policies to enhance food security in diverse contexts.

Table 2 – Identified drivers and their impact on the 6 food security pillars.

Category	Driver	Short- or Long-term impact	The driver can be influenced in a reasonable time by	Food Security Pillars						References
				Availability	Access	Utilization	Stability	Agency	Sustainability	
Main	Biophysical and Environmental									
Subcategory	Changing climate and weather patterns, natural disasters									
Variable	Temperature changes	Both	None	(+)(−)	(−)	(−)	(−)	(−)	(−)	Islam & Wong, 2017; Chen et al., 2017; El Samra, 2017; Firdaus et al., 2020
Variable	Precipitation changes	Both	None	(+)(−)	(−)		(−)		(−)	Islam & Wong, 2017; El Samra, 2017; IPCC, 2019; Firdaus et al., 2020; Ebrahimi et al., 2023
Variable	Extreme weather events (droughts, heatwaves, heavy precipitation, hurricanes, tornados, extreme winds, floods, etc.)	Both	None	(−)	(−)	(−)	(−)	(−)	(−)	Desta & Coppock, 2002; Nkedianye et al., 2011; FAO, 2015 Islam & Wong, 2017; Chen et al., 2017; El Samra, 2017; IPCC, 2019; Oskorouchi & Sousa-Poza, 2020; Hobbins et al., 2023
Variable	Natural disasters (e.g., fire, earthquake)	Both	Policymaker	(−)	(−)	(−)	(−)	(−)	(−)	Kawamura et al., 2008; Vassiliadou et al., 2009; Johnson, 2011; IPCC, 2019; Oskorouchi et al., 2020

Category	Driver	Short- or Long-term impact	The driver can be influenced in a reasonable time by	Food Security Pillars						References
				Availability	Access	Utilization	Stability	Agency	Sustainability	
Variable	Atmospheric CO2 levels	Long	Policymaker	(+)(−)		(−)			(−)	Islam & Wong, 2017; El Samra, 2017; Firdaus et al., 2020
Variable	Changes in water availability and quality	Both	Policymaker	(−)	(−)	(−)	(−)		(−)	Hanjra & Qureshi, 2010; FAO, 2015; Islam & Wong, 2017; El Samra, 2017; IPCC, 2019; Hobbins et al., 2023
Variable	Climate change mitigation policies	Long	Policymaker	(+)	(+)(−)	(+)	(+)	(+)(−)	(+)	IPCC, 2019; Firdaus et al., 2020
Subcategory	Environmental pollution									
Variable	Air pollution	Both	Policymaker	(−)	(+)(−)	(−)	(+)(−)	(−)	(−)	Van Dingenen et al., 2009; Tai et al., 2014; Feng et al., 2015; Tai & Val Martin, 2017; Sun et al., 2017; Vysochyna et al., 2020; Sonwani & Saxena, 2022; Xia et al., 2023
Variable	Air quality legislation	Long	Policymaker	(+)	(+)	(+)	(+)	(+)	(+)	Van Dingenen et al., 2009; Tai et al., 2014; Bertolozzi-Caredio et al., 2023; EC, 2023c
Variable	Water pollution	Both	Policymaker	(−)	(−)	(−)	(−)	(−)	(−)	Lu et al., 2015; Islam & Wong, 2017; Morales-Muñoz et al., 2020; Vysochyna et al., 2020; Xia et al., 2023; Marriott et al., 2023; Irfeey et al., 2023

Category	Driver	Short- or Long-term impact	The driver can be influenced in a reasonable time by	Food Security Pillars						References
				Availability	Access	Utilization	Stability	Agency	Sustainability	
Variable	Improved manure management	Both	Company	(+)	(+)	(+)	(+)	(+)	(+)	Ndambi et al., 2019; Rurinda et al., 2020; Köninger et al., 2021; Marriott et al., 2023
Subcategory	Soil health									
Variable	Soil contamination	Both	Policymaker	(-)	(-)	(-)	(-)	(-)	(-)	FAO, 2018; Hou et al., 2020.; Larramendy & Soloneski, 2021; Silatsa & Kebede, 2023
Variable	Soil erosion	Long	None	(-)	(-)	(-)	(-)	(-)	(-)	Pimentel, 2006; Bakker et al., 2007; Costea et al., 2022; Yu & Deng, 2022
Variable	Soil nutrient depletion	Long	Company	(-)	(-)	(-)	(-)	(-)	(-)	Tan et al., 2005; Drechsel et al., 2001; Bayu, 2012; Radosavljevic et al., 2020; Ocwa et al., 2023; Musa et al., 2024
Variable	Soil organic carbon loss	Long	Company	(+)(-)	(-)	(-)	(-)	(-)	(+)(-)	Lal, 2005; Waqas et al., 2020; Yu & Deng, 2022; Ma et al., 2023
Variable	Soil restoration initiatives	Both	Policymaker	(+)	(+)	(+)	(+)	(+)	(+)	Silatsa & Kebede, 2023
Variable	Land degradation	Long	None	(-)	(-)		(-)	(-)	(-)	Blaikie & Brookfield, 1987; Hamdy & Aly, 2014; Barbier & Hochard, 2018; Woolf et al., 2018; Pozza & Field, 2020; Ocwa et al.,

Category	Driver	Short- or Long-term impact	The driver can be influenced in a reasonable time by	Food Security Pillars						References
				Availability	Access	Utilization	Stability	Agency	Sustainability	
										2023; Silatsa & Kebede, 2023
Subcategory	Natural resources and biodiversity									
Variable	Agricultural biodiversity changes	Both	Company	(+)(−)	(+)(−)	(+)(−)	(+)(−)	(+)(−)	(+)(−)	Thrupp, 2000; Frison et al., 2011; Fedotova et al., 2021
Variable	Biodiversity changes in the natural environment	Both	None	(+)(−)	(+)(−)	(+)(−)	(+)(−)	(+)(−)	(+)(−)	Jansson & Polasky 2010; Jiren et al., 2020; Behnassi & Gupta, 2022; Jankielsohn, 2023
Variable	Marine biodiversity changes	Both	Company	(+)(−)	(+)(−)	(+)(−)	(+)(−)	(+)(−)	(+)(−)	Duarte, 2000; EC, 2023c; Manzolli et al., 2024
Variable	Pollination services	Both	Policymaker	(+)(−)	(+)(−)	(+)(−)	(+)(−)	(+)(−)	(+)(−)	Kevan & Viana, 2003; van der Sluijs & Vaage, 2016; Porto et al., 2020; EC, 2023c
Variable	Nutrient cycling	Short	Company	(+)(−)	(+)(−)	(+)(−)	(+)(−)	(+)(−)	(+)(−)	Jarvie et al., 2015; Rowe et al., 2016; Choudhary et al., 2018; Salwan & Sharma, 2022
Variable	Water degradation and scarcity	Both	Company	(−)	(−)		(−)		(−)	Falkenmark, 2001; Rosegrant et al., 2009; Sethi et al., 2013; Merrey, 2015; Gomiero, 2016; Croke & Jewitt, 2018; Lundqvist & Unver, 2020

Category	Driver	Short- or Long-term impact	The driver can be influenced in a reasonable time by	Food Security Pillars						References
				Availability	Access	Utilization	Stability	Agency	Sustainability	
Variable	Crop protection and pesticides	Both	Company	(+)(−)	(+)(−)	(+)(−)	(+)(−)	(+)(−)	(+)(−)	Popp et al., 2013; Mahmood et al., 2016; Bertolozzi-Caredio et al., 2023; EC, 2023c
Subcategory	Pests, invasive species, diseases and pandemics									
Variable	Natural pest control	Long	Policymaker	(+)(−)	(+)(−)	(+)(−)	(+)(−)	(+)(−)	(+)(−)	Petit et al., 2020; EC, 2023
Variable	Invasive species	Both	Company	(−)	(−)	(−)	(−)	(−)	(−)	Bertolozzi-Caredio et al., 2023
Variable	Plant pests and diseases	Both	Company	(−)	(−)	(−)	(−)	(−)	(−)	Shafik et al., 2023; Bertolozzi-Caredio et al., 2023; EC, 2023c
Variable	Animal diseases	Both	Policymaker	(−)	(−)	(−)	(−)	(−)	(−)	Peeler & Ernst, 2019; Cerbu et al., 2023; Bertolozzi-Caredio et al., 2023
Variable	Pandemics	Both	Policymaker	(−)	(−)	(−)	(−)	(−)	(−)	Pillay & Scheepers 2020; Sarkar et al., 2021; Thomas et al., 2022; Kumar, 2023
Variable	Pest management practices	Long	Company	(+)	(+)	(+)	(+)	(+)	(+)	EC, 2023; Avila et al., 2023
Subcategory	Ecosystem Restoration and Sustainable Farming Practices									
Variable	Conservation agriculture practices	Long	Company	(+)	(+)	(+)	(+)	(+)	(+)	Giller et al., 2009; Dahal et al., 2009; Ogundari, 2014; Vira et al., 2015; Marambe et al., 2020; Onono et al., 2021; Cárceles Rodríguez et al., 2022

Category	Driver	Short- or Long-term impact	The driver can be influenced in a reasonable time by	Food Security Pillars						References
				Availability	Access	Utilization	Stability	Agency	Sustainability	
Variable	Organic farming methods	Long	Company	(+)(-)	(+)	(+)	(+)	(+)	(+)(-)	Lorenz & Lal, 2016; Saravia-Matus et al., 2016; Udemezue et al., 2019; Boone et al., 2019; Gamage et al., 2023; Expósito, 2023; Gupta & Pandey, 2023; Sutardi et al., 2023;
Variable	Agroecological approaches	Long	Company	(+)	(+)	(+)	(+)	(+)	(+)	Wezel et al., 2014; Valluru et al., 2015; Tambo et al., 2020; Mutungi et al., 2023
Variable	Soil carbon sequestration	Long	Company	(+)	(+)	(+)	(+)	(+)	(+)	Lal, 2004; 2016; Mwavu et al., 2018; Reilly et al., 2016; Jha et al., 2022; Upadhyay et al., 2023
Subcategory	Fisheries and Aquaculture									
Variable	Overfishing	Both	Policymaker	(-)	(-)	(-)	(-)	(-)	(-)	Garcia & Rosenberg, 2010
Variable	Illegal, unreported, and unregulated (IUU) fishing	Short	Policymaker	(-)	(-)	(-)	(-)	(-)	(-)	Garcia & Rosenberg, 2010
Variable	Changes in the marine environment	Long	None	(-)	(-)				(-)	Garcia & Rosenberg, 2010; Lancker et al., 2019
Variable	Poor fisheries management	Long	Company	(-)	(-)	(-)	(-)	(-)	(-)	Garcia & Rosenberg, 2010
Variable	Marine use conflicts	Long	Policymaker	(-)	(-)	(-)	(-)	(-)	(-)	Lancker et al., 2019
Variable	Increasing reliance on fisheries for coastal developing countries	Long	Policymaker	(+)	(+)	(+)	(-)	(-)	(-)	Lancker et al., 2019

Category	Driver	Short- or Long-term impact	The driver can be influenced in a reasonable time by	Food Security Pillars						References
				Availability	Access	Utilization	Stability	Agency	Sustainability	
Subcategory	Competing land and crop uses									
Variable	Biofuel policies	Both	Policymaker	(−)	(+)(−)	(−)	(−)	(−)	(+)(−)	Thomas et al., 2009; HLPE, 2013; Koizumi, 2014; 2015; Kline et al., 2016; Araujo Enciso et al., 2016; Naylor & Higgins, 2018; Gasparatos et al., 2022
Variable	Livestock production	Long	Policymaker	(−)					(−)	Koizumi, 2015; Wu, 2017; Mekuria et al., 2018; Yessymkhanova et al., 2021
Main	Technology, innovation, and supply chain									
Subcategory	Research, innovation, information & technology									
Variable	Governance and institutional research	Long	Policymaker	(+)	(+)(−)	(+)(−)	(+)	(+)	(+)(−)	Wassmann et al., 2019; Manikas et al., 2022; Farrukh et al., 2022; Wudil et al., 2022; Cassimon et al., 2023; Javeed et al., 2023; Bai et al., 2023; Munialo et al., 2024
Variable	Social innovation	Long	Policymaker	(+)	(+)	(+)	(+)	(+)	(+)	Elmes, 2018; EEA, 2022; Bertolozzi-Caredio et al., 2023; EC, 2023
Variable	Business model innovation	Both	Company	(+)(−)	(+)(−)	(+)(−)	(+)(−)	(+)(−)	(+)(−)	Hamam et al., 2021; Manikas et al., 2022; WEF, 2022; Yadav et al., 2023;

Category	Driver	Short- or Long-term impact	The driver can be influenced in a reasonable time by	Food Security Pillars						References
				Availability	Access	Utilization	Stability	Agency	Sustainability	
Variable	Information and technology solutions	Both	Company	(+)	(+)(−)	(+)		(+)(−)	(+)	Elmes, 2018; Torero, 2021; WEF, 2022; 2022b; WB, 2022 Gondal et al., 2023; Yadav et al., 2023;
Variable	Advances in energy technologies	Both	Company	(+)	(+)	(+)	(+)	(+)	(+)	WFP, 2002; Saqib et al., 2023; Ukobaa et al., 2024; Rehman et al., 2024
Variable	Technological advances in crop resistance	Long	Company	(+)		(+)			(+)(−)	Wassmann et al., 2019; Mores et al., 2021; Giménez-Ibánez, 2021
Variable	Automation	Both	Company	(+)	(+)(−)	(+)	(+)(−)	(−)	(+)(−)	Caldwell, 2018; Torero, 2021; Gondal et al., 2023; Demircioglu et al., 2024
Subcategory	Supply chain performance									
Variable	Transportation Infrastructure	Both	Policymaker	(+)(−)	(+)(−)		(−)	(−)	(−)	Keating, 2013; Svanidze et al., 2019; Volz et al., 2020; Kovaleva et al., 2022; EC, 2023; Kozielec et al., 2024
Variable	Equipment and facility management (maintenance, equipment failure, service life, incorrect operation/process hazards, material failures)	Short	Company	(−)	(−)	(−)	(−)	(−)	(−)	Nastasijević et al., 2017; Polukhin et al., 2021; Lennnoen et al., 2022; Bertolozzi-Caredio et al., 2023; Bartáková et al., 2023; Pakdel et al., 2023
Variable	Logistics operations	Short	Company	(+)(−)	(+)(−)	(+)(−)	(−)	(+)(−)		Keating, 2013; Abbade, 2020; Marusak et al., 2021; EC, 2023c

Category	Driver	Short- or Long-term impact	The driver can be influenced in a reasonable time by	Food Security Pillars						References
				Availability	Access	Utilization	Stability	Agency	Sustainability	
Variable	Non-flexibility to change	Long	Company	(-)	(-)	(-)	(-)	(-)	(-)	EC, 2023c
Variable	Cyber-attacks and internet blackouts	Short	Company	(-)	(-)	(-)	(-)	(-)	(-)	Chundhoo et al., 2021; Arya et al., 2023; Moersdorf et al., 2023; Bertolozzi-Caredio et al., 2023; Alqudhaibi et al., 2024
Variable	Technical/technological risk	Long	Policymaker	(-)	(-)	(-)		(-)	(-)	Bahn et al., 2021; Zscheischler et al., 2022; Bertolozzi-Caredio et al., 2023
Variable	Input availability	Short	Company	(+)(-)	(+)(-)	(-)	(-)	(-)		Prasad, 2009; Sola et al., 2016; Nsiah et al., 2019; Mahlknecht et al., 2020; EC, 2023; Penuelas et al., 2023; Hebebrand & Debucquet, 2023
Subcategory	Food loss									
Variable	Inadequate storage conditions	Short	Company	(-)	(-)	(-)	(-)		(+)	Premanandh, 2011; Canali et al., 2017; Blakeney, 2019; Magalhaes et al., 2021; Warsame et al., 2022; Das et al., 2023; EC, 2023; Hosseini et al., 2024
Variable	Processing and packaging	Short	Company	(+)(-)	(-)					Tapsoba et al., 2022; Paraschivu et al., 2022;

Category	Driver	Short- or Long-term impact	The driver can be influenced in a reasonable time by	Food Security Pillars						References
				Availability	Access	Utilization	Stability	Agency	Sustainability	
										Bertolozzi-Caredio et al., 2023
Variable	Food contamination	Short	Company	(-)	(-)	(-)	(-)	(-)	(-)	Pinior et al., 2015; Ghosh et all., 2016; Sheahan & Barrett, 2017; García-Díez et al., 2021; Cattaneo et al., 2021; Bertolozzi-Caredio et al., 2023; EC, 2023; WHO, 2024
Main	Market and economic									
Subcategory	Financial									
Variable	Energy market speculation	Short	Policymaker	(-)	(-)		(+)(-)			Pasqualino et al., 2019; EC, 2023
Variable	Financialization of commodities	Short	Policymaker	(+)(-)	(+)(-)		(+)(-)	(-)	(+)(-)	Herman et al., 2011; Kalkuhl et al., 2016; Staugaitis & Vaznonis, 2022; Fama & Conti, 2022; Isakson et al., 2023
Variable	Input costs and farm-gate prices	Short	Company	(+)(-)	(-)		(+)(-)		(-)	Mushtaq et al., 2009; Beckman et al., 2020; Bertolozzi-Caredio et al., 2023; EC, 2023c
Variable	Macroeconomic factors	Long	Policymaker	(+)(-)	(+)(-)	(-)	(+)(-)	(-)	(-)	Saravia-Matus et al., 2012; Sage, 2013; Islam et al., 2017; Beckman et al., 2020; EC, 2023
Variable	Global economic trends	Long	Policymaker	(-)	(+)(-)	(-)	(+)(-)			EC, 2023

Category	Driver	Short- or Long-term impact	The driver can be influenced in a reasonable time by	Food Security Pillars						References
				Availability	Access	Utilization	Stability	Agency	Sustainability	
Variable	Access to finance and lack of resources	Both	Policymaker	(−)	(−)	(−)	(−)	(−)	(−)	Fama & Conti, 2022; Huang & Azman, 2023; EC, 2023c
Variable	Financial liquidity (lack of)	Both	Policymaker	(−)	(−)		(−)		(−)	Chang et al., 2014; Millimet et al., 2018; Fama & Conti, 2022; EC, 2023
Variable	Financial and economic crisis	Both	Policymaker	(−)	(−)	(−)	(−)		(−)	Hanjra et al., 2010; Bertolozzi-Caredio et al., 2023
Variable	Market price volatility	Short	Policymaker	(−)	(−)	(−)	(−)	(−)	(−)	Kalkuhl et al., 2016; Firdaus et al., 2019; Bertolozzi-Caredio et al., 2023; EC, 2023c
Variable	Farm income	Short	Policymaker	(+)(−)	(+)(−)	(+)(−)	(+)(−)	(+)(−)	(+)(−)	Corsi et al., 2017; Herrmann et al., 2018; Oluwatayo, 2019; Fredriksson et al., 2021; Moreno-Pérez et al., 2023; Huang & Azman, 2023
Subcategory	Market									
Variable	Market forces	Both	Policymaker	(+)(−)	(+)(−)	(−)	(−)	(−)	(+)(−)	Khan et al., 2009; Sage, 2013; El Samra, 2017; Staugaitis et al., 2022; Fama & Conti, 2022; Mabiso et al., 2014; EC, 2023c

Category	Driver	Short- or Long-term impact	The driver can be influenced in a reasonable time by	Food Security Pillars						References
				Availability	Access	Utilization	Stability	Agency	Sustainability	
Variable	Access	Both	Policymaker	(+)	(+)	(+)	(+)	(+)		Mabiso et al., 2014; Peyton et al., 2015; Zulfiqar, 2017; Saravia-Matus et al., 2022; Nkegbe & Mumin, 2022; Hellegers, 2022; Madsen, 2022; Tojo-Mandaharisoa et al., 2023
Variable	Liquidity	Long	Policymaker	(+)(−)	(+)(−)		(−)			Yi et al., 2014; Staugaitis & Vaznonis, 2022; Bertolozzi-Caredio et al., 2023; Tojo-Mandaharisoa et al., 2023;
Variable	Contraction, concentration, and unfair competition	Long	Policymaker	(−)	(+)(−)		(−)	(+)(−)	(−)	Sasson, 2012; Peyton et al., 2015; Wahyu et al., 2016; Blažková, 2016; Bertolozzi-Caredio et al., 2023
Variable	Global demand and supply dynamics	Both	None	(+)(−)	(−)	(+)	(+)(−)	(+)(−)	(+)(−)	Sasson, 2012; Abdulkadyrova et al., 2016; Elzaki, 2023; EC, 2023
Variable	Agri- and consumer food prices	Both	Policymaker	(+)(−)	(+)(−)	(+)(−)	(+)(−)	(+)(−)	(+)(−)	Timmer, 2012; Gustafson, 2013; Mabiso et al., 2014; Kalkuhl et al., 2016; Kwaw-Nimeson, & Tian, 2021; Elzaki, 2023; EC, 2023c
Subcategory	Energy supply and prices									
Variable	Global energy demand	Both	Policymaker	(−)	(−)		(−)		(+)(−)	Müller, 2008; Karp et al., 2011; Dias, 2016;

Category	Driver	Short- or Long-term impact	The driver can be influenced in a reasonable time by	Food Security Pillars						References
				Availability	Access	Utilization	Stability	Agency	Sustainability	
										Taghizadeh-Hesary et al., 2019; Hasegawa et al., 2020; EC, 2023c
Variable	Supply disruptions	Short	Company	(-)	(-)	(-)	(-)	(-)		Reddy et al., 2016; Voss et al., 2022; Dias, 2016; Bertolozzi-Caredio et al., 2023; EC, 2023; Chepeliev et al., 2023; Ostashko, 2024
Variable	Integrating renewable energy sources	Both	Company	(+)	(+)	(+)	(+)		(+)	Dias, 2016; Weselek et al., 2019; Qu et al., 2021; Gorjian et al., 2022; Rabbi et al., 2023; Bertolozzi-Caredio et al., 2023
Subcategory	Trade									
Variable	Trade integration and liberalization	Long	Policymaker	(+)	(+)(-)	(+)	(+)(-)	(+)		Bonuedi et al., 2020; Van Berkum, 2021; Barros & Martínez-Zarzoso, 2022; Ibrahim et al., 2023; EC, 2023
Variable	Trade agreements	Both	Policymaker	(+)	(+)	(+)	(+)(-)	(-)	(+)	McCorriston et al., 2013; Bouët and Laborde, 2017; Sun and Zhang, 2021; van Berkum, 2021; Barros & Martínez-Zarzoso, 2022; Bertolozzi-Caredio et al.,

Category	Driver	Short- or Long-term impact	The driver can be influenced in a reasonable time by	Food Security Pillars						References
				Availability	Access	Utilization	Stability	Agency	Sustainability	
										2023; Brewer et al., 2023; EC, 2023c; Wang et al., 202; FAO, 2024
Variable	Global trade dynamics	Long	Policymaker	(+)(−)	(+)(−)	(+)(−)	(+)(−)	(+)(−)	(+)(−)	Regmi & Meade, 2013; LI et al., 2021; Rother et al., 2022; Bertolozzi-Caredio et al., 2023; Brewer et al., 2023; EC, 2023; Wang et al., 2021; 2023
Variable	Barriers and disruptions	Both	Policymaker	(+)(−)	(−)	(−)	(+) (−)	(−)	(−)	Lopes et al., 2019; Bonuedi et al., 2020; Kituyi, 2020; Cao et al., 2021; Zhang & Zhou, 2023; Bertolozzi-Caredio et al., 2023; EC, 2023c; De Vos et al., 2023; Plavšić (2023)
Variable	Import dependency	Long	Policymaker	(−)	(−)		(−)			Lopes et al., 2019; Luo & Tanaka, 2021; Ghalibaf et al., 2022; Brewer et al., 2023; Bertolozzi-Caredio et al., 2023; EC, 2023c; Peng et al., 2024
Variable	Export-oriented production	Long	Company	(+)(−)	(+)(−)	(−)	(−)			EC, 2023c; Aragie et al., 2023
Subcategory	Labor									
Variable	Availability of workers	Both	Policymaker	(+)(−)	(+)(−)	(−)	(−)	(−)	(−)	Burchi & De Muro, 2016; Martin, 2020; Bertolozzi-

Category	Driver	Short- or Long-term impact	The driver can be influenced in a reasonable time by	Food Security Pillars						References
				Availability	Access	Utilization	Stability	Agency	Sustainability	
										Caredio et al., 2023; EC, 2023; FSA, 2023; González-Moralejo ET AL., 2024
Variable	Aging trend in the agricultural workforce	Long	None	(−)	(−)	(−)	(−)	(−)	(−)	Bertolozzi-Caredio et al., 2023; EC, 2023c; Zhang et al., 2023
Variable	Training programs	Both	Company	(+)(−)	(+)	(+)		(+)	(+)(−)	Gondwe et al., 2017; García-Díez et al., 2021; EC, 2023; Zhang et al., 2023
Subcategory	Household resources									
Variable	Economic growth	Long	Policymaker	(+)	(+)	(+)			(−)	French et al., 2019; Hakeem et al., 2023; Tackie et al., 2023
Variable	Social protection policies	Short	Policymaker	(+)	(+)(−)	(−)	(+)	(+)	(+)	Mutisya et al., 2015; Ogunniyi et al. (2021); Awoyemi et al., 2023; Osabohien et al., 2023
Variable	Poverty reduction	Long	None		(+)		(+)(−)	(+)		Martin, 2010; Alam et al., 2018; Berthe et al., 2019
Variable	Income inequality	Long	Policymaker		(−)	(−)	(−)	(−)		Holleman & Conti, 2020; Nyakundi et al., 2020; Banaie et al., 2023
Main	Political and Institutional									
Subcategory	Legislative framework									

Category	Driver	Short- or Long-term impact	The driver can be influenced in a reasonable time by	Food Security Pillars						References
				Availability	Access	Utilization	Stability	Agency	Sustainability	
Variable	Policy changes and regulatory environment	Long	Policymaker	(+)(−)	(+)(−)		(+)(−)	(+)(−)	(+)(−)	Lusk et al., 2011; Miewald et al., 2013; Qureshi et al., 2015; Mohr et al., 2016; Walls et al., 2018; Obayelu et al., 2020; Pavleska & Kerr, 2020; Wahbeh et al., 2022; Sundram, 2023
Variable	Subsidies	Both	Policymaker	(+)	(+)(−)	(+)	(+)(−)	(−)	(−)	Black et al., 2012; Kostadinov, 2013; Solaymani et al., 2019; Wahbeh et al., 2022
Variable	Public policy intervention	Long	Policymaker	(+)	(+)	(+))(−)	(+)	(+)	(+)	Cleary et al., 2018; Thow et al., 2018; Pavleska & Kerr, 2020; Wahbeh et al., 2022
Variable	Back-up systems to prevent interruptions in food availability	Short	Company	(+)(−)	(+)(−)	(+)(−)	(+)(−)	(+)(−)	(+)(−)	Moosavi, & Hosseini, 2021; Wahbeh et al., 2022
Subcategory	Governance and institutional									
Variable	National and international governance	Both	Policymaker	(+)(−)	(+)(−)	(+)	(+)	(−)	(+)	Shiferaw & Holden, 1997; Bindraban et al., 2012; Kostadinov, 2013; Belesky, 2014; Brown, 2014; Maystadt et al., 2014; Zimmermann et al., 2018; Candel, 2018; Cerrada-Serra et al., 2018
Variable	Crisis response mechanisms	Both	Policymaker	(+)	(+)	(+)	(+)	(+)	(+)	Brown, 2014; Webb et al., 2014; Rembold et al., 2019;

Category	Driver	Short- or Long-term impact	The driver can be influenced in a reasonable time by	Food Security Pillars						References
				Availability	Access	Utilization	Stability	Agency	Sustainability	
										Krishnamurthy, 2020; Amjath-Babu et al., 2023
Variable	Complexity of global food systems	Long	None	(+)(−)	(+)(−)	(+)(−)	(+)(−)	(+)(−)	(+)(−)	Allen, 2015; Candel, 2018; Davila et al., 2018; Rembold et al., 2019
Subcategory	Geopolitical instability, conflict, and terrorism									
Variable	Political crises	Short	None	(−)	(−)		(−)	(−)	(−)	De Laurentiis et al., 2016; El-Jafari et al., 2019; George & Adelaja, 2022; Oderinde et al., 2022; Minten et al., 2023; Abis & Demurtas, 2023
Variable	Geopolitical events	Both	None	(+)(−)	(+)(−)	(−)	(−)			El-Jafari et al., 2019; George & Adelaja, 022; Abis & Demurtas, 2023; Podkolzina et al., 2023
Variable	Armed conflict	Both	None	(−)	(−)	(−)	(−)	(−)	(−)	Hendrix & Brinkman, 2013; El-Jafari et al., 2019; Martin-Shields & Stojetz, 2019; George & Adelaja, 2022; Munialo & Mellor, 2023; Messer et al., 2024
Variable	Intercommunal conflicts	Both	Policymaker	(−)	(−)		(−)	(−)	(−)	George & Adelaja, 2022
Variable	Corruption	Both	None	(−)	(−)	(−)	(−)	(−)	(−)	Uchendu & Abolarin, 2015; Santangelo, 2017; Nugroho et al., 2022; Bertolozzi-Caredio et al.,

Category	Driver	Short- or Long-term impact	The driver can be influenced in a reasonable time by	Food Security Pillars						References
				Availability	Access	Utilization	Stability	Agency	Sustainability	
										2023; Demeshko et al., 2024
Variable	Social disorders and unrest	Both	None	(–)	(–)		(–)			Hendrix & Brinkman, 2013; Bertolozzi-Caredio et al., 2023; EC, 2023
Variable	Terrorism	Both	None	(–)	(–)	(–)	(–)	(–)	(–)	Adelaja & George, 2019; George et al., 2019; George & Adelaja, 2022
Variable	Intentional malicious acts	Both	Company	(–)	(–)	(–)	(–)	(–)	(–)	Manning & Soon, 2016; Gahukar, 2014; Guiné et al., 2021; Grundy et al., 2023; Yeasmin et al., 2023; Bertolozzi-Caredio et al., 2023; EC, 2023
Main	Socio-cultural and demographic									
Subcategory	Demographic trends									
Variable	Population growth	Long	None	(+)(–)	(–)	(–)	(–)		(–)	Duda et al., 2018; Kousar et al., 2021; Tekwa, 2022
Variable	Urbanization	Long	None	(+)(–)	(–)	(–)	(–)	(–)	(–)	Crush & Tawodzera, 2017; Kousar et al., 2021; Tekwa, 2022
Variable	Aging population	Long	None		(+)	(–)	(–)		(–)	Sun-Waterhouse et al., 2014; Tekwa, 2022
Variable	Migration and displacement	Both	Policymaker	(+)(–)	(+)(–)	(+)(–)	(+)(–)	(+)(–)	(+)(–)	Hammelman, 2018; Obi et al., 2020; Keswani, 2021; Kousar et al., 2021;

Category	Driver	Short- or Long-term impact	The driver can be influenced in a reasonable time by	Food Security Pillars						References
				Availability	Access	Utilization	Stability	Agency	Sustainability	
										Orjuela-Grimm et al., 2022; Grauel & Chambers, 2023;
Subcategory	Generational renewal									
Variable	Access to land	Long	Policymaker	(+)(−)	(+)(−)		(+)(−)	(+)(−)	(+)(−)	Mahon, 2012; Żmija et al., 2020; Skrzypczyński et al., 2021
Variable	Access to credit	Both	Policymaker	(+)(−)	(+)(−)		(+)(−)	(+)(−)		Loring & Gerlach, 2015; Eistrup et al., 2019; Micha et al., 2019; Żmija et al., 2020
Variable	Lifestyle-oriented reasons	Long	None	(−)				(+)(−)	(−)	Loring & Gerlach, 2015; Żmija et al., 2020
Subcategory	Consumer preferences and food choices									
Variable	Economic factors	Short	Policymaker	(+)(−)	(+)(−)				(−)	Kumar et al., 2020; Jacob et al., 2023
Variable	Social and cultural factors	Long	None		(−)	(+)(−)		(+)(−)	(+)	Regmi & Gehlhar, 2001; Arnalte-Mul et al., 2020; Jacob et al., 2023; Randall et al., 2024
Variable	Health, nutrition, and dietary changes	Long	None		(−)	(+)(−)		(+)(−)	(+)	Seed et al., 2013; Sandoval et al., 2020; Schurr, 2020; Kumar et al., 2020; Jacob et al., 2023; Grauel & Chambers, 2023; Randall et al., 2024
Variable	Hunger and obesity	Long	None	(−)	(−)	(−)	(−)	(−)		Amorim et al., 2022; Jacob et al., 2023

Category	Driver	Short- or Long-term impact	The driver can be influenced in a reasonable time by	Food Security Pillars						References
				Availability	Access	Utilization	Stability	Agency	Sustainability	
Variable	Marketing and advertising	Short	Policymaker	(+)(−)	(+)(−)	(−)		(+)(−)		Kumar et al., 2020; Amorim et al., 2022; Jacob et al., 2023; Arrona-Cardoza et al., 2023; Arnolds, 2023; Agurs-Collins et al., 2024
Variable	Education and awareness	Long	Policymaker	(+)(−)	(+)(−)	(+)(−)	(+)(−)	(+)(−)	(+)(−)	Mutisya et al., 2016; Mancini et al., 2017; Ragasa et al., 2019; Arnalte-Mul et al., 2020; Mabe et al., 2021; Oluwatayo et al., 2021; Jacob et al., 2023
Subcategory	Food waste through consumption									
Variable	Excess buying	Short	Policymaker	(−)	(−)			(−)	(−)	Balan et al., 2022; Irani & Sharif, 2016; EC, 2023
Variable	Portioning and package sizes	Short	Company	(−)	(−)			(−)	(−)	Wohner et al., 2019; Irani & Sharif, 2016; EC, 2023
Variable	Confusion over labels	Short	Company		(−)			(−)	(−)	Irani & Sharif, 2016; Kavanaugh & Quinlan, 2020; Bertolozzi-Caredio et al., 2023
Variable	Inadequate in-home storage	Short	Policymaker		(−)	(−)			(−)	Tomaszewska et al., 20222; Balan et al., 2022; Irani & Sharif, 2016; EC, 2023
Variable	Cultural attitudes towards food waste	Long	None		(−)			(−)	(−)	Balan et al., 2022; Irani & Sharif, 2016; EC, 2023

4.2.1 Biophysical and Environmental

Changing climate and weather patterns, natural disasters

The impacts of changing climate and weather patterns and natural disasters on the six pillars of food security are multifaceted, with both positive and negative consequences. In the short term, extreme weather events such as droughts, floods, and heatwaves negatively affect availability by damaging crops, livestock, and fisheries, reducing food supply and raising prices, which limits access, especially for vulnerable populations (Islam & Wong, 2017; Oskorouchi & Sousa-Poza, 2020). However, in some cases, climate changes may extend the growing seasons or allow the cultivation of crops in areas previously unsuitable due to cooler temperatures, thereby potentially increasing food availability (IPCC, 2019; Chen et al., 2017). On the other hand, negative impacts on utilization arise as extreme weather events can contaminate food supplies and water sources, reducing food quality and safety (El Samra, 2017). Furthermore, the stability of food systems is generally compromised by the increasing frequency and intensity of natural disasters, which disrupt supply chains and food production cycles, leading to fluctuations in food availability and market volatility (Islam & Wong, 2017; FAO, 2015). Nonetheless, improved climate adaptation measures, such as the development of resilient infrastructure and crop diversification, can enhance stability by mitigating some of the adverse effects of climate change (Firdaus et al., 2020; Ebrahimi et al., 2023). While these events negatively impact agency, limiting the capacity of farmers and fishers to plan and manage production, climate adaptation strategies like resilient crop cultivation empower these groups to better manage risks in changing conditions (Ebrahimi et al., 2023).

In the long term, climate change presents opportunities and challenges for food security. Rising atmospheric CO2 levels may enhance photosynthesis and crop growth, potentially increasing food availability in certain regions (Islam & Wong, 2017; Chen et al., 2017). However, this positive effect is often outweighed by the negative consequences, such as increased vulnerability to pest and disease outbreaks, which can damage crops and reduce yields (Hanjra & Qureshi, 2010). Similarly, while shifting precipitation patterns may improve water availability in some areas, prolonged droughts or flooding in others can lead to water stress, undermining both agricultural productivity and long-term sustainability (IPCC, 2019; Hobbins et al., 2023). Additionally, climate change often leads to the degradation of natural resources, such as soil erosion and biodiversity loss, which threatens the long-term sustainability of food systems and reduces the ability of ecosystems to support ongoing food production (FAO, 2015). However, adaptation strategies, such as adopting climate-resilient crops and sustainable land management practices, can help protect the sustainability of food systems and empower farmers with more outstanding agencies to manage climate risks effectively (El Samra, 2017; Ebrahimi et al., 2023). Thus, while the overall impact of climate change on food security is predominantly negative, proactive adaptation and mitigation strategies can harness potential positive effects and safeguard food systems for the future.

Environmental pollution

In the short term, air pollution, particularly from ozone and particulate matter, negatively impacts agricultural productivity, reducing food availability. Ozone pollution, particularly, has been shown to reduce crop yields by up to 10%, affecting essential staples such as wheat and contributing to global food insecurity (Van Dingenen et al., 2009; Tai et al., 2014; Feng et al., 2015; Tai & Val Martin, 2017). These reductions in yield directly affect food access, particularly in regions already vulnerable to food shortages. Furthermore, air pollution contributes to poor food utilization as contaminated crops may lead to foodborne illnesses, exacerbating malnutrition and health problems (Sun et al., 2017; Xia et al., 2023). The stability of food systems is also compromised by air pollution, as climate variability and pollution exacerbate the unpredictability of crop yields (Vysochyna et al., 2020). Additionally, pollution undermines the agency of farmers by limiting their control over natural resources and agricultural outputs (Sonwani & Saxena, 2022).

In the long term, air and water pollution threaten the sustainability of food systems. Nitrogen and ammonia deposition, for example, degrade soil quality, reducing the long-term fertility of agricultural lands and leading to further declines in crop productivity (Xia et al., 2023). Water pollution exacerbates these challenges, as contaminated water sources reduce the availability of clean water for irrigation, which is essential for maintaining crop health (Lu et al., 2015; Morales-Muñoz et al., 2020; Marriott et al., 2023). However, practical measures such as air quality legislation and improved manure management offer pathways to reduce pollution levels and these negative consequences. Air quality legislation aimed at reducing emissions and improving environmental conditions can significantly enhance food availability and stability by protecting crop yields from the harmful effects of pollution (Van Dingenen et al., 2009; Tai et al., 2014; Bertolozzi-Caredio et al., 2023; EC, 2023c). Similarly, improved manure management practices can enhance soil quality, increase crop yields, and reduce the environmental footprint of agricultural practices by promoting sustainable nutrient recycling (Ndambi et al., 2019; Rurinda et al., 2020; Köninger et al., 2021). While environmental pollution poses severe threats to food security, targeted interventions such as policy reform and sustainable agricultural practices can contribute to a more resilient and sustainable food system (Marriott et al., 2023).

Soil Health

Soil health plays a fundamental role in determining food security. Soil contamination, caused by pesticides, heavy metals, and industrial waste, significantly reduces food availability by degrading soil fertility and crop productivity. As contaminants accumulate in the soil, they hinder plant growth, resulting in lower yields and decreased agricultural land availability (FAO, 2018; Hou et al., 2020). This decline in productivity restricts access to food, especially in regions reliant on subsistence farming, where soil contamination undermines the quantity and quality of agricultural yields (Larramendy & Soloneski, 2021). Moreover, soil contamination negatively affects food utilization, as crops grown in polluted soils may contain harmful substances that pose health risks to consumers, including cancer and neurological disorders (Silatsa & Kebede, 2023). The long-term presence of these pollutants also destabilizes food production systems, as contaminated soils remain unproductive for years, making it difficult to restore their fertility (FAO, 2018). Farmers lose agency when faced with contaminated soils, as their capacity to cultivate healthy, productive land diminishes, further jeopardizing the sustainability of agricultural systems (Hou et al., 2020).

Soil erosion, another critical driver, significantly impacts food security. The loss of nutrient-rich topsoil through erosion diminishes agricultural productivity and food availability, reducing the soil's capacity to support crop growth (Pimentel, 2006; Bakker et al., 2007). Erosion also limits access to food by increasing the cost of farming due to the need for additional inputs, such as fertilizers, which may not fully compensate for the loss of soil fertility (Costea et al., 2022). Nutrient-poor crops resulting from soil erosion negatively affect food utilization, as they are less nutritious and lower in quality (Yu & Deng, 2022). The instability caused by soil erosion extends beyond the farm, impacting food systems by reducing the reliability of food supplies (Pimentel, 2006). Farmers, particularly those in erosion-prone areas, lose agency as their ability to manage and maintain productive soils decreases with each erosion season (Bakker et al., 2007). Over time, soil erosion threatens the sustainability of agricultural systems by continuously depleting the land's productive capacity, making future food production more challenging (Costea et al., 2022). Initiatives aimed at restoring soil health, such as reforestation and sustainable land management, can play a vital role in reversing the effects of soil degradation, thereby enhancing both short- and long-term food security (Silatsa & Kebede, 2023). Implementing these measures is critical to preserving soil health, ensuring stable food systems, and promoting sustainable agricultural practices (Blaikie & Brookfield, 1987; Silatsa & Kebede, 2023).

Natural resources and biodiversity

Agricultural biodiversity supports food availability by enhancing crop yields, resilience, and overall agricultural productivity. Diverse farming systems provide higher yields, greater resilience to pests, diseases, and climate variability, and promote sustainable farming practices that enhance food production (Thrupp, 2000; Frison et al., 2011). Agricultural biodiversity promotes food utilization by offering diverse diets that improve nutrition and health outcomes. For example, diverse farming systems provide nutrient-rich crops critical for balanced diets (Frison et al., 2011; Fedotova et al., 2021). Pollination services, which are essential for many crops, further support food availability and utilization by ensuring the successful reproduction of food plants. An estimated 87% of global crops rely on animal pollination, which contributes to the stability and quality of food production (Kevan & Viana, 2003; Porto et al., 2020; EC, 2023c). Natural biodiversity also strengthens ecosystem services like nutrient cycling, improving soil health and agricultural productivity, and supporting the long-term sustainability of food systems (Jarvie et al., 2015; Salwan & Sharma, 2022).

Conversely, the degradation of biodiversity and natural resources harms food security. Loss of agricultural biodiversity reduces food availability by diminishing crop yields and the resilience of farming systems. This loss limits the ability of ecosystems to support diverse, nutritious food sources, directly impacting food access and utilization (Thrupp, 2000; Frison et al., 2011). For instance, the decline in pollinator populations leads to reduced crop yields and threatens food availability and nutritional diversity (van der Sluijs & Vaage, 2016; Porto et al., 2020). Additionally, the degradation of marine biodiversity has far-reaching impacts on food security by reducing the availability of seafood, a vital food source for many populations (Duarte, 2000; EC, 2023c). Overfishing and pollution disrupt marine ecosystems, compromising food systems' sustainability and stability (Manzolli et al., 2024). Water degradation exacerbates these challenges by reducing water availability for irrigation, negatively impacting agricultural productivity and food availability (Falkenmark, 2001; Rosegrant et al., 2009). Heavy reliance on pesticides also threatens long-term sustainability, as their overuse can lead to soil degradation, water pollution, and the loss of biodiversity, ultimately reducing the resilience and sustainability of food production systems (Popp et al., 2013; Mahmood et al., 2016; EC, 2023). Thus, maintaining biodiversity and the health of natural resources is essential for the long-term viability of global food security.

Pests, invasive species, diseases and pandemics

Plant pests and diseases reduce food availability by causing significant crop losses, leading to food shortages and price fluctuations. These challenges are particularly critical in regions heavily dependent on agriculture, where the spread of pathogens and pests destabilizes food systems and decreases the quality of available food (Shafik et al., 2023; Bertolozzi-Caredio et al., 2023; Petit et al., 2020; EC, 2023c). Invasive species exacerbate these issues by disrupting local ecosystems, outcompeting native species, and reducing biodiversity, further undermining agricultural systems' stability and limiting crop productivity (Bertolozzi-Caredio et al., 2023). Animal diseases threaten food availability by reducing livestock production, affecting access to essential animal-based nutrients like meat and milk. These diseases reduce supply and pose serious health risks to consumers through the contamination of animal products, impacting food utilization (Peeler & Ernst, 2019; Cerbu et al., 2023; Bertolozzi-

Caredio et al., 2023). The collective impact of these challenges diminishes farmers' agency as they struggle to maintain control over their production, often turning to unsustainable practices, such as overuse of antimicrobials and pesticides, which compromise long-term sustainability (Bertolozzi-Caredio et al., 2023).

In the long term, pandemics severely disrupt food security by destabilizing supply chains, limiting food access, and reducing labour availability for food production. The COVID-19 pandemic exemplified these impacts, where mobility restrictions and workforce shortages led to food shortages, increased prices, and reduced access to food for vulnerable populations. Moreover, pandemics negatively affect food utilization by disrupting the supply of diverse and nutritious food, leading to poorer dietary quality for affected communities. Effective pest management practices, such as integrated pest management, offer sustainable solutions to these challenges by reducing reliance on chemical pesticides and promoting ecological balance. These strategies protect crop yields, enhance food stability, and contribute to the long-term sustainability of food systems (EC, 2023c; Avila et al., 2023). Natural pest control methods, in particular, play a crucial role in maintaining ecosystem health and supporting resilient agricultural systems by minimizing the need for chemical interventions while ensuring stable food production (Petit et al., 2020; EC, 2023c).

Ecosystem restoration and sustainable farming practices

Ecosystem restoration and sustainable farming practices, such as conservation agriculture, organic farming, agroecological approaches, and soil carbon sequestration, have significant short- and long-term impacts on food security. By enhancing soil health through minimal soil disturbance and cover cropping, conservation agriculture directly boosts food availability by increasing crop yields and reducing soil erosion (Giller et al., 2009; Dahal et al., 2009; Ogundari, 2014). These practices improve access to food by stabilizing yields and making farming more resilient to climate variations, particularly in regions susceptible to adverse climatic conditions (Vira et al., 2015; Marambe et al., 2020). Additionally, conservation agriculture positively impacts food utilization by producing healthier soils that support nutrient-rich crops, which are safer and more nutritious for consumers (Onono et al., 2021; Cárceles Rodríguez et al., 2022). Organic farming methods contribute to food access by fostering diverse production systems and reducing dependence on chemical inputs, making food production more sustainable in the long term (Lorenz & Lal, 2016; Saravia-Matus et al., 2016; Gupta & Pandey, 2023). However, these methods can sometimes lead to reduced yields in the short term, affecting immediate availability (Boone et al., 2019; Expósito, 2023).

In the long term, agroecological approaches play a critical role in enhancing food system sustainability by promoting biodiversity and reducing the need for synthetic fertilizers and pesticides, which helps protect ecosystems and ensures long-term food availability (Wezel et al., 2014; Valluru et al., 2015; Tambo et al., 2020). Agroecological practices also empower farmers by giving them more control over their farming systems and fostering greater independence from external inputs (Mutungi et al., 2023). Soil carbon sequestration further strengthens sustainability by improving soil fertility and capturing carbon, which mitigates climate change and enhances food security (Lal, 2004; 2016; Reilly et al., 2016). Practices such as agroforestry and no-till farming increase the soil's carbon content, resulting in higher crop yields and more resilient farming systems in the long run (Mwavu et al., 2018; Upadhyay et al., 2023). Though the transition to these sustainable farming methods may pose challenges, such as initial investments or temporary reductions in productivity, the long-term benefits—improved soil health, enhanced ecosystem services, and greater resilience—ultimately contribute to stable and sustainable food systems (Jha et al., 2022).

Fisheries and Aquaculture

Fisheries enhance food availability by providing a steady supply of fish and seafood, a critical protein source for millions worldwide. However, some drivers can threaten this source of food supply over the long run. For instance, overfishing depletes fish stocks, reducing availability and threatening food security in regions dependent on marine resources. Illegal, unreported, and unregulated (IUU) fishing often hinders access to fish resources, undermining equitable access to aquatic resources, particularly for small-scale fishers in coastal developing countries. Utilization is affected when poor fisheries management leads to lower-quality fish or contamination, compromising the nutritional value of fish as a food source (Garcia & Rosenberg, 2010). Instability arises from fluctuations in fish populations due to overfishing and environmental changes, affecting the consistency of the fish supply (Lancker et al., 2019). Due to poor fisheries management, diminished agencies exacerbate the problem, as local stakeholders often lose control of overfishing resources and decision-making (Garcia & Rosenberg, 2010).

In the long term, unsustainable fishing practices threaten the sustainability of fish stocks and marine ecosystems. Overfishing depletes current stocks and jeopardizes the future availability of marine resources, worsening food security for coastal communities heavily reliant on fisheries (Garcia & Rosenberg, 2010). Changes in the aquatic environment, including habitat degradation and climate-induced shifts, further reduce the availability and access to fish (Garcia & Rosenberg, 2010; Lancker et al., 2019). The lack of effective fisheries management amplifies the issue by failing to implement sustainable practices supporting long-term fish stock health (Garcia & Rosenberg, 2010). Conflicts over marine resource use, exacerbated by increasing competition between commercial and small-scale fishers, further limit access and destabilize fish populations (Lancker et al., 2019). Ultimately, the combination of overfishing, IUU fishing, and poor management diminishes stakeholders' control over resources, leading to a loss of agency and threatening the sustainability of fisheries for future generations (Garcia & Rosenberg, 2010).

Competing land and crop uses

The competition for land and crop use, driven by biofuel policies and livestock production, significantly impacts the six pillars of food security: availability, access, utilization, stability, agency, and sustainability. In the short term, biofuel policies have reduced the availability of crops for human consumption by diverting land to biofuel and feedstock production, particularly for crops like corn, soybean oil, and palm oil, which are essential in many diets (Thomas et al., 2009; HLPE, 2013; Koizumi, 2014). This shift in land use also limits access to these vital food resources by increasing prices, disproportionately affecting low-income populations (Naylor & Higgins, 2018; Gasparatos et al., 2022). The environmental consequences of biofuel-driven land conversion, including deforestation and soil degradation, further destabilize food production systems, thereby threatening long-term food sustainability (Kline et al., 2016; Araujo Enciso et al., 2016).

In the long term, the expansion of livestock production exacerbates the competition for land, as large areas are converted for grazing and feed production, leading to deforestation and loss of agricultural biodiversity (Koizumi, 2015; Wu, 2017). This intensification of land use for livestock contributes to soil degradation, which decreases agricultural land's long-term productivity and undermines food production systems' stability (Mekuria et al., 2018; Yessymkhanova et al., 2021). Moreover, this competition for land between biofuel feedstocks and livestock reduces farmers' agency, as they have less control over how land is managed due to policy incentives for biofuels and increased demand for livestock products (Koizumi, 2015). Ultimately, these competing land uses threaten the long-term sustainability of food systems by depleting natural resources and compromising the capacity of future generations to maintain food production (Thomas et al., 2009; Gasparatos et al., 2022).

4.2.2 Technology, Innovation and Supply Chain

Research, Innovation, Information and Technology

In the short term, improved agricultural practices driven by research and technological advancements increase crop yields, enhancing food availability. Governance and institutional research contribute to this by promoting better land management and resource allocation, fostering increased agricultural productivity, and ensuring efficient resource utilization (Wassmann et al., 2019; Farrukh et al., 2022; Wudil et al., 2022). Social innovation initiatives, such as community-based cooperatives, improve access to knowledge and technology for marginalized groups, enhancing food production and availability (Elmes, 2018; Bertolozzi-Caredio et al., 2023). Additionally, business model innovations can help expand market access and affordability through sustainable value chains, positively impacting availability and food access (Hamam et al., 2021; Yadav et al., 2023). However, implementing these innovations can sometimes exacerbate inequalities if certain groups do not have equal access to new technologies, limiting their impact on access and agency (WEF, 2022).

In the long term, technological advances like early warning systems and climate-resilient technologies promote stability in food systems by mitigating the effects of climate change and extreme weather events (Torero, 2021; Gondal et al., 2023). Improved crop resistance, supported by research on disease-resistant crops, helps safeguard food availability by reducing losses from pests and diseases (Wassmann et al., 2019; Giménez-Ibánez, 2021). Advances in energy technologies, such as solar-powered cooling and renewable energy in agriculture, contribute to sustainability by reducing greenhouse gas emissions and preserving food quality, especially for perishable goods (WFP, 2002; Rehman et al., 2024), for instance, by providing a continuous energy supply and avoiding interruptions in the cold chain. Automation technologies, while enhancing productivity and efficiency, may create challenges related to job displacement and reduced agency for low-skilled laborers (Torero, 2021; Demircioglu et al., 2024). Overall, research and technological innovations are critical in driving improvements in food security, but their equitable distribution and careful management are essential to ensuring long-term sustainability and inclusivity in food systems (Elmes, 2018; WEF, 2022).

Supply Chain Performance

Supply chain performance is a critical driver in shaping food security. In the short term, the quality of transportation infrastructure is crucial for ensuring the timely delivery of food products, especially perishable goods, directly affecting availability (Keating, 2013; Svanidze et al., 2019). Efficient logistics operations can also improve access to food by ensuring that markets are well-stocked, reducing gaps in the supply chain (Keating, 2013; Abbade, 2020). However, disruptions in transportation networks or poor infrastructure can lead to food spoilage during transit, negatively affecting utilization and reducing the nutritional value of food products (Volz et al., 2020; Kovaleva et al., 2022). Additionally, poor equipment and facility management can cause failures that disrupt the supply chain, leading to shortages and impacting stability and food access (Nastasijević et al., 2017; Polukhin et al., 2021). Failures in cold storage or other handling systems also shorten the shelf life of food, further reducing utilization (Bartáková et al., 2023).

In the long term, disruptions in supply chain performance, such as those caused by cyber-attacks or technical failures, pose a significant threat to stability and sustainability in food systems (Chundhoo et al., 2021; Bertolozzi-Caredio et al., 2023). Cyber-attacks on critical infrastructure or logistics networks could severely disrupt food production and distribution, reducing availability and access (Arya et al., 2023). These risks also limit the agency of stakeholders, as farmers and suppliers become dependent on increasingly complex technologies vulnerable to external threats (Moersdorf et al., 2023). Moreover, the reliance on fossil-fuel-based transport systems contributes to environmental degradation, posing a long-term challenge to sustainability unless more sustainable transport solutions are adopted (Bahn et al., 2021; EC, 2023c). Investments in energy-efficient practices, such as renewable energy in transport and cold storage, are crucial for improving sustainability and reducing the environmental impact of supply chains (WFP, 2002; Saqib et al., 2023). Overall, supply chain performance can enhance or hinder food security depending on the infrastructure's resilience, management, and ability to adapt to emerging risks (Prasad, 2009; Sola et al., 2016).

Food Loss

Food loss is a critical driver that impacts food security. In the short term, inadequate storage conditions contribute significantly to food loss, particularly for perishable goods, reducing availability by preventing food from reaching consumers. Poor storage conditions result in spoilage, especially in regions with limited infrastructure, directly reducing the amount of food available for distribution (Premanandh, 2011; Canali et al., 2017). This also negatively affects access, as less food reaches markets, raising prices and further limiting access, especially for vulnerable populations (Blakeney, 2019; Warsame et al., 2022). Processing and packaging innovations can play a role in mitigating these losses by extending the shelf life of food products, improving availability and access through longer preservation, and reducing spoilage (Tapsoba et al., 2022; Paraschivu et al., 2022). Conversely, food contamination incidents, often related to improper storage or handling, can exacerbate food loss, affecting availability and reducing consumer trust, thus affecting access and utilization (Pinior et al., 2015; García-Díez et al., 2021). Contaminated food, when discarded, also leads to significant waste, which undermines efforts to improve food security (Ghosh et al., 2016).

In the long term, addressing food loss is essential for promoting stability and sustainability in food systems. Reducing food loss helps stabilize supply chains by minimizing fluctuations in food availability, thereby preventing price hikes and ensuring more reliable food access for consumers (Magalhaes et al., 2021). Improving storage conditions and investing in efficient packaging solutions can significantly enhance the stability of food systems, making food more available and affordable in the long run (Hosseini et al., 2024). Additionally, reducing food loss impacts sustainability by minimizing the waste of natural resources, such as water and energy, used in food production (Canali et al., 2017). Advances in processing technologies that extend the shelf life of food prevent waste and improve sustainability by ensuring that food can be stored and consumed over extended periods, thus reducing environmental impacts (Bertolozzi-Caredio et al., 2023). However, contamination remains a persistent issue, leading to immediate and long-term losses that affect the overall efficiency of food systems and the sustainability of food production (Sheahan & Barrett, 2017; WHO, 2024).

4.2.3 Market and Economic

Financial

In the short term, the financialization of commodities can have a mixed impact on availability and access. While futures markets provide a mechanism for balancing supply and demand, excessive speculation can amplify price volatility, leading to sudden price spikes that reduce food affordability and access, especially for vulnerable populations (Herman et al., 2011; Kalkuhl et al., 2016). The financial instability caused by such speculation can also affect food producers, who may make suboptimal decisions based on unpredictable market conditions, leading to reduced agricultural output and instability in food availability (Pasqualino et al., 2019; Staugaitis & Vaznonis, 2022). Meanwhile, input costs, such as fertilizers or energy, continue rising due to global economic conditions. Higher input costs directly strain farm production by limiting the resources farmers can allocate to improve yields, reducing availability and food access (Mushtaq et al., 2009; Bertolozzi-Caredio et al., 2023). Additionally, macroeconomic factors like inflation or currency fluctuations can reduce consumer purchasing power, further exacerbating food insecurity by making it more difficult for low-income households to afford basic staples (Saravia-Matus et al., 2012; EC, 2023).

In the long term, smallholder farmers' lack of access to finance hinders investments in sustainable agricultural practices, impacting food systems' sustainability and stability (Huang & Azman, 2023). Financial liquidity is crucial for supporting the adoption of modern farming technologies, which help improve crop yields and ensure a stable food supply. However, when financial liquidity is constrained, farmers face incredible difficulty accessing necessary inputs, negatively affecting availability, utilization, and agency (Chang et al., 2014; Fama & Conti, 2022). Price volatility, driven by market speculation and global economic trends, can further destabilize the agricultural sector, undermining long-term sustainability and increasing the risk of food shortages (Firdaus et al., 2019; EC, 2023c). Financial crises, such as the 2008 Credit Crisis, demonstrated how reduced capital flow to the agricultural sector could lead to decreased food production and higher food prices, diminishing access to food for both producers and consumers (Hanjra et al., 2010; Bertolozzi-Caredio et al., 2023). In addition, the long-term sustainability of food systems is threatened when financial factors push farmers to adopt unsustainable practices to maintain profitability, further contributing to environmental degradation and reduced agricultural resilience (EC, 2023c). Thus, addressing financial challenges is essential for ensuring long-term stability, availability, and sustainability of global food systems.

Market

In the short term, efficient market dynamics can positively affect food availability by improving distribution systems and incentivizing agricultural production (Khan et al., 2009; Mabiso et al., 2014). Access to food is also enhanced when diverse food products are available through competitive markets, ensuring that consumers have a wide variety of options at affordable prices (Peyton et al., 2015; Zulfiqar, 2017). However, market forces can also create barriers for marginalized groups, such as small-scale farmers, who may struggle to compete with larger agribusinesses. This reduces agency and unequal market access (El Samra, 2017; Fama & Conti, 2022). Additionally, the financialization of commodities can lead to price volatility, disproportionately affecting low-income consumers and small producers by increasing food prices and reducing their ability to afford basic staples (Staugaitis et al., 2022; Kalkuhl et al., 2016). Market failures, such as monopolies or excessive speculation, further exacerbate these issues by destabilizing food supply chains and creating instability in food availability and access (Herman et al., 2011; Mabiso et al., 2014).

In the long term, global market dynamics can affect the sustainability of food systems by driving agricultural practices prioritizing short-term profitability over long-term environmental health. For example, increased demand for biofuels has driven land use changes, diverting land from food production and contributing to environmental degradation, ultimately threatening food availability and sustainability (Sage, 2013; EC, 2023c). Furthermore, global demand and supply imbalances can lead to fluctuations in agricultural prices, which affect stability by creating uncertainty in the availability of essential food commodities (Abdulkadyrova et al., 2016; Elzaki, 2023). Over time, the concentration of market power among a few large agribusinesses can reduce competition, limit access for smaller producers, and stifle innovation, thereby threatening long-term sustainability and reducing consumer choice (Sasson, 2012; Bertolozzi-Caredio et al., 2023). However, well-regulated markets that foster transparency, fair competition, and equitable access to resources can enhance food security by improving agricultural productivity, stabilizing food prices, and ensuring that food systems are resilient to shocks (Mabiso et al., 2014; Nkegbe & Mumin, 2022). Thus, while market forces can enhance food security, they also carry risks that must be managed through appropriate governance and regulation to ensure stability, access, and sustainability over time (El Samra, 2017; Mabiso et al., 2014).

Energy Supply & Prices

In the short term, fluctuations in global energy demand can significantly affect food availability and access by increasing production and transportation costs. Higher energy prices, driven by increased international demand, elevate costs for agricultural producers, reducing the availability and access to food due to constrained production and higher consumer prices (Müller, 2008; Karp et al., 2011; Dias, 2016). As energy is essential for powering irrigation systems, food storage, and transport, supply disruptions exacerbate this issue, particularly in low- and middle-income countries, which are more vulnerable to energy shocks (Reddy et al., 2016; Voss et al., 2022). These disruptions can destabilize supply chains, affecting the stability of food systems and the accessibility of nutritious food for vulnerable populations (Chepeliev et al., 2023; EC, 2023c). The reliance on fossil fuels also has negative implications for sustainability, as the environmental degradation caused by greenhouse gas emissions undermines long-term agricultural productivity (Dias, 2016; Taghizadeh-Hesary et al., 2019).

In the long term, integrating renewable energy sources into agricultural systems offers promising solutions for enhancing food security across multiple pillars. By reducing dependency on non-renewable energy, renewable energy sources, such as agrivoltaics and biogas, can improve the stability of food systems by ensuring a more reliable energy supply, even during disruptions to traditional energy sources (Dias, 2016; Weselek et al., 2019; Qu et al., 2021). This shift to renewables reduces production costs by limiting exposure to volatile fuel prices and promotes sustainability by decreasing the carbon footprint of food production (Gorjian et al., 2022; Bertolozzi-Caredio et al., 2023). Renewable energy sources can improve access and utilization by making food production more efficient and environmentally friendly, supporting healthier food systems, and reducing environmental damage (Rabbi et al., 2023). However, achieving these benefits requires inclusive energy policies and community involvement to ensure that the transition to renewable energy fosters agency and equitable outcomes for all stakeholders (Bertolozzi-Caredio et al., 2023).

Trade

In the short term, trade integration and liberalization can significantly boost food availability by facilitating the flow of agricultural products from surplus to deficit regions, ensuring that food reaches areas that may otherwise face shortages (Bonuedi et al., 2020; Van Berkum, 2021). This cross-border exchange also promotes access by providing consumers with diverse food products, often at more affordable prices, due to competitive market forces (Barros & Martínez-Zarzoso, 2022; EC, 2023c). However, reliance on trade can introduce vulnerabilities, as countries heavily dependent on imports face increased exposure to global price fluctuations and supply disruptions (Lopes et al., 2019; Brewer et al., 2023). These disruptions, whether caused by geopolitical tensions or climate-related events, can reduce the availability and affordability of food, particularly for vulnerable populations (Cao et al., 2021; Kituyi, 2020). Moreover, trade agreements that favour large agribusinesses can marginalize small-scale farmers, limiting their agency and undermining their ability to compete in the global market (Bouët & Laborde, 2017; Bertolozzi-Caredio et al., 2023).

In the long term, global trade dynamics and the implementation of favourable trade agreements can stabilize food systems by ensuring a consistent flow of essential commodities and reducing market volatility (Regmi & Meade, 2013; Wang et al., 2023). However, trade liberalization can also lead to overreliance on export-oriented production, which diverts resources away from domestic food production, negatively affecting the stability and sustainability of local food systems (EC, 2023c; Aragie et al., 2023). While export revenues can boost national income and improve access to imported foods, an excessive focus on exports may leave domestic markets vulnerable to food insecurity, significantly if global demand shifts or supply chains are disrupted (Luo & Tanaka, 2021; Brewer et al., 2023). Trade barriers and disruptions, such as tariffs and non-tariff measures, can exacerbate these risks by increasing the cost of imports and limiting access to essential food supplies (Zhang & Zhou, 2023; Bertolozzi-Caredio et al., 2023). Therefore, while trade integration can enhance food security, its long-term benefits depend on careful management to ensure that trade policies promote economic growth, local food sovereignty, and sustainability (Van Berkum, 2021; EC, 2023c).

Labor

In the short term, providing a skilled and adequately compensated labour force enhances agricultural productivity, increasing food availability and access. Well-trained workers are crucial for improving crop yields, efficiently managing post-harvest practices, and ensuring that food reaches markets on time, reducing waste and spoilage (Burchi & De Muro, 2016; Martin, 2020; Bertolozzi-Caredio et al., 2023). Additionally, labour shortages, particularly in labor-intensive industries such as agriculture, can reduce production, resulting in higher food prices and reduced consumer availability (FSA, 2023). The lack of available workers also affects food supply chain stability, as shortages in critical roles such as truck drivers and warehouse personnel can disrupt food distribution and limit market access (González-Moralejo et al., 2024). Moreover, fair wages and good working conditions can empower workers, increase access to nutritious food, and improve their agency over food security (EC, 2023c).

In the long term, the aging agricultural workforce presents significant challenges to food security, particularly regarding availability and sustainability. As older workers retire, the agricultural sector faces a shortage of experienced labour, leading to decreased productivity and the potential abandonment of arable land (Bertolozzi-Caredio et al., 2023; Zhang et al., 2023). This demographic shift can reduce food availability and exacerbate instability in the supply chain as fewer younger workers enter the agricultural workforce. Training programs are crucial in addressing these challenges by equipping younger generations with the skills to adopt modern farming techniques, improve productivity, and enhance agricultural sustainability (Gondwe et al., 2017; García-Díez et al., 2021). However, if training programs and labour policies do not adequately address the workforce gaps, the long-term sustainability of food systems could be compromised, with negative impacts on availability, utilization, and stability (Zhang et al., 2023). Ensuring that young workers are attracted to and retained in agriculture through training, fair wages, and career development opportunities is essential for maintaining a skilled, resilient, and sustainable labour force supporting all pillars of food security (EC, 2023c).

Household Resources

Economic growth improves food security in the short term by increasing household income. It positively impacts four pillars of food security—availability, access, utilization, and stability—by increasing household income. With higher income, families can invest in agricultural inputs and technology that immediately improve food production and availability (French et al., 2019; Hakeem et al., 2023). Increased household income also enhances access by boosting purchasing power, enabling families to afford a wider variety of nutritious foods, contributing to dietary diversity and better nutrition (Tackie et al., 2023). Additionally, social protection measures, such as cash transfers and food vouchers, help improve food access and stability for low-income households, acting as short-term buffers against economic shocks that could otherwise jeopardize food security (Mutisya et al., 2015; Awoyemi et al., 2023). However, disparities in income can limit the equitable distribution of these benefits, with lower-income households facing continued struggles to afford nutritious food, exacerbating short-term food insecurity (Nyakundi et al., 2020; Holleman & Conti, 2020).

In the long term, the emphasis shifts toward achieving stability and sustainability in food security, where poverty reduction becomes essential for consistent access to food and resilience against future economic fluctuations. Reducing poverty allows households to build resources gradually, enabling sustained investment in food production and reducing reliance on short-term solutions (Martin, 2010; Alam et al., 2018). Long-term poverty alleviation also supports stable food systems by ensuring households maintain access to food even during economic downturns, fostering community resilience (Berthe et al., 2019). However, persistent income inequality poses a significant threat to these goals, as it restricts access to food for the most vulnerable, perpetuating disparities in nutrition and food quality (Nyakundi et al., 2020; Banaie et al., 2023). Targeted social protection programs that address income inequality contribute to long-term food security by empowering marginalized communities to actively participate in and benefit from sustainable food systems (Ogunniyi et al., 2021; Osabohien et al., 2023). Without addressing inequality, food security efforts' long-term stability and sustainability—especially in low- and middle-income countries—remain at risk (Holleman & Conti, 2020).

4.2.4 Political and Institutional

Legislative Framework

Effective policy changes and a well-designed regulatory environment can improve food availability in the short term by promoting sustainable agricultural practices and ensuring food safety standards (Lusk et al., 2011; Pavleska & Kerr, 2020). Public policy interventions, such as subsidies for smallholder farmers, enhance access to resources like seeds, fertilizers, and technology, supporting agricultural productivity and ensuring that food reaches markets (Cleary et al., 2018; Wahbeh et al., 2022). However, poorly designed or inadequate legislation may perpetuate inequalities by limiting access to land and resources for marginalized groups, reducing agency, and increasing food insecurity (Mohr et al., 2016; Qureshi et al., 2015). Additionally, weak enforcement of food safety regulations can result in contamination risks, undermining consumer trust and negatively impacting food utilization (Miewald et al., 2013; Obayelu et al., 2020).

In the long term, the effectiveness of the legislative framework in promoting food security depends on its ability to ensure sustainability and resilience in food systems. Subsidies promoting environmentally friendly farming practices can enhance long-term agricultural sustainability by encouraging adopting practices that reduce environmental degradation (Solaymani et al., 2019; Wahbeh et al., 2022). On the other hand, poorly targeted subsidies may favour unsustainable farming methods, contributing to soil degradation and biodiversity loss, undermining the sustainability of food systems (Black et al., 2012; Kostadinov, 2013). Moreover, the implementation of robust back-up systems to prevent disruptions in food availability, such as during natural disasters or supply chain breakdowns, can stabilize food systems and mitigate the risks of food shortages (Moosavi & Hosseini, 2021; Wahbeh et al., 2022). Ultimately, a legislative framework that balances market regulation, environmental sustainability, and equitable resource access can foster stability, empower stakeholders, and ensure the long-term sustainability of global food systems (Walls et al., 2018; Sundram, 2023).

Governance and Institutional

In the short term, effective national and international governance can positively impact food availability by promoting policies that enhance agricultural productivity and ensure equitable resource distribution (Shiferaw & Holden, 1997; Bindraban et al., 2012). International cooperation and agreements can help maintain food reserves and stabilize supply during times of crisis, ensuring that food remains available even during shortages (Belesky, 2014; Zimmermann et al., 2018). Moreover, strong governance can improve access by fostering inclusive policies that support vulnerable populations through subsidies, income support, and social protection measures, enhancing their ability to purchase food (Maystadt et al., 2014; Cerrada-Serra et al., 2018). However, inadequate governance or weak regulatory frameworks can perpetuate inequality, allowing for corruption and mismanagement, which undermines food access and increases food insecurity, particularly in marginalized regions (Kostadinov, 2013; Brown, 2014).

In the long term, the effectiveness of governance and institutions determines the sustainability and resilience of food systems. Well-coordinated crisis response mechanisms can stabilize food systems by mitigating the effects of external shocks such as climate change or market disruptions, ensuring long-term food stability (Webb et al., 2014; Rembold et al., 2019). National policies that promote sustainable land management and resource allocation can enhance sustainability by preventing environmental degradation and preserving natural resources vital for future food production (Candel, 2018; Davila et al., 2018). However, ineffective governance structures or lack of institutional collaboration can exacerbate the complexity of global food systems, hindering the adoption of long-term strategies that address sustainability and resilience (Allen, 2015; Candel, 2018). Additionally, governance challenges such as protectionist policies or poorly designed trade regulations can disrupt food markets, leading to price volatility and threatening food access and stability in the long run (Rembold et al., 2019; Krishnamurthy, 2020). Thus, strong governance and institutional frameworks are essential for fostering collaboration, promoting sustainability, and ensuring the long-term stability of global food systems (Cerrada-Serra et al., 2018; Amjath-Babu et al., 2023).

Geopolitical Instability, Conflict, and Terrorism

In the short term, political crises, particularly armed conflict, disrupt agricultural production by damaging crops, livestock, and infrastructure, significantly reducing food availability (De Laurentiis et al., 2016; El-Jafari et al., 2019). Such conflicts hinder transportation routes and destroy supply chains, leading to essential food product shortages and limiting market access (George & Adelaja, 2022). Additionally, conflicts often trigger economic downturns and job losses, further reducing people's purchasing power and undermining access to food (Oderinde et al., 2022). Terrorist activities exacerbate these issues by directly targeting food production, distribution networks, and markets, creating instability and fear that affect people's ability to make secure food choices (Adelaja & George, 2019). As a result, the utilization pillar is compromised due to disrupted access to safe, nutritious food (Manning & Soon, 2016). Furthermore, the uncertainty and volatility caused by political upheavals and social unrest create market instability, leading to price fluctuations and further reducing the availability of affordable food (Minten et al., 2023).

In the long term, conflicts and political instability impede sustainable development efforts and hinder investments in agricultural infrastructure and innovation, which are essential for ensuring food systems' long-term stability and sustainability (El-Jafari et al., 2019). Prolonged geopolitical instability reduces agricultural productivity by displacing farming populations, destroying farmlands, and creating environmental degradation, mainly through deforestation and the depletion of water resources (George & Adelaja, 2022). This leads to reduced availability of arable land, threatening future food production and sustainability (Podkolzina et al., 2023). Additionally, the reliance on aid during prolonged conflicts diminishes local agencies as affected populations depend on external assistance rather than self-sufficient farming practices (Martin-Shields & Stojetz, 2019). Corruption during crises further exacerbates food insecurity by diverting resources meant for agricultural development, limiting access to essential food supplies, and promoting inequality in food distribution (Uchendu & Abolarin, 2015; Santangelo, 2017). Ultimately, the environmental degradation caused by conflict, combined with insufficient governance and poor resource management, threatens the long-term sustainability of food production, leaving affected regions more vulnerable to future food crises (Hendrix & Brinkman, 2013). Without proper interventions, the impacts of geopolitical instability, conflict, and terrorism will continue to undermine the pillars of food security, particularly in fragile states.

4.2.5 Socio-cultural and Demographic

Demographic Trends

In the short term, favourable demographic trends, such as population growth in regions with untapped agricultural potential, can positively impact food availability by increasing agricultural labour and productivity (Duda et al., 2018; Kousar et al., 2021). The growing workforce can drive innovation and enhance food production, addressing local food demand and generating market opportunities (Tekwa, 2022). However, rapid population growth in densely populated areas can strain food systems, as increased demand for food, land, and resources can reduce availability and create competition over agricultural inputs (Kousar et al., 2021). This pressure on resources may lead to food insecurity, particularly in urban areas where infrastructure may not meet the growing demand (Crush & Tawodzera, 2017). Additionally, as populations age in certain regions, there is a greater need for social welfare programs to support food access for vulnerable elderly groups, which may temporarily improve access and stability (Sun-Waterhouse et al., 2014). However, age-related health issues could hinder nutrient utilization among aging populations, posing challenges to dietary adequacy and affecting food utilization (Tekwa, 2022).

In the long term, rapid urbanization and migration trends can have mixed effects on food security. Urbanization tends to reduce agricultural land availability, decrease food production, and negatively affect food availability (Crush & Tawodzera, 2017; Tekwa, 2022). The shift from rural to urban areas also disrupts traditional food systems, creating instability in food supply chains and resulting in reliance on market-based food systems that limit agency, especially for rural communities (Kousar et al., 2021). Migration and displacement, on the other hand, can positively impact availability and access by addressing labour shortages in agricultural sectors through migrant workers who fill critical roles in food production (Hammelman, 2018; Keswani, 2021). This influx of labour can enhance stability by ensuring consistent production and contributing to the long-term viability of agricultural systems (Grauel & Chambers, 2023). However, restrictive migration policies and poor working conditions for migrant labourers can undermine sustainability, as reliance on temporary or unstable labour creates vulnerability in the agricultural workforce (Orjuela-Grimm et al., 2022). In addition, displacement due to conflicts or environmental crises further disrupts food systems, affecting stability and limiting long-term sustainability (Obi et al., 2020). Thus, addressing demographic trends requires a balanced approach that considers their immediate and future impacts on all pillars of food security.

Generational renewal

The availability of land for young farmers is essential for increasing agricultural productivity and ensuring the continued food supply. Providing access to land to young farmers is frequently associated with the adoption of innovative farming methods, contributing to the efficient use of resources and increasing food production (Mahon, 2012; Żmija et al., 2020; Skrzypczyński et al., 2021). However, the high cost of land, coupled with limited availability, hinders many young farmers from entering the agricultural sector, reducing their ability to contribute to food availability and overall food security (Żmija et al., 2020). Similarly, access to credit allows young farmers to invest in necessary inputs, machinery, and infrastructure, boosting food production and ensuring market access (Loring & Gerlach, 2015; Eistrup et al., 2019). Without sufficient financial support, young farmers face challenges in sustaining their operations, which threatens the stability of food systems and limits their agency in agricultural decision-making (Micha et al., 2019). Lifestyle preferences also affect generational renewal, as younger generations often view farming as less attractive than other sectors, exacerbating labour shortages and reducing agricultural productivity (Żmija et al., 2020).

In the long term, generational renewal is critical for the sustainability and resilience of agricultural systems. Young farmers bring new skills, innovations, and sustainable practices, which contribute to the long-term viability of farming businesses and help mitigate the effects of climate change and environmental degradation (Mahon, 2012; Skrzypczyński et al., 2021). Access to land empowers young farmers by giving them control over their agricultural decisions and enabling them to build resilient food systems. However, land fragmentation and competition with other land uses often limit the ability of young farmers to expand their operations, negatively affecting long-term food availability and sustainability (Żmija et al., 2020). Access to credit is equally essential for long-term sustainability, as it allows farmers to make investments that improve productivity and reduce income volatility during market fluctuations (Loring & Gerlach, 2015; Micha et al., 2019). Without access to credit, young farmers are more vulnerable to economic shocks, which undermines the stability of food systems and limits their ability to implement sustainable practices (Eistrup et al., 2019). Finally, lifestyle preferences that deter younger generations from pursuing careers in agriculture pose long-term risks to food security, as they reduce labour availability and limit innovation in the agricultural sector (Żmija et al., 2020). Thus, ensuring access to land, credit, and career opportunities in agriculture is essential for sustaining food systems and addressing the challenges of generational renewal in the long term.

Consumer Preferences and Food Choices

In the short term, consumer preferences for nutritious, diverse, and sustainably produced foods can boost the availability of healthier and environmentally friendly products, determining a shift in producers' choices (Kumar et al., 2020). Consumer advocacy for organic, locally sourced, and fair-trade products supports small-scale farmers and promotes sustainable agriculture, contributing to increased food access and the resilience of food systems (Jacob et al., 2023). This shift in demand enhances utilization by promoting healthier diets and better nutritional outcomes, particularly as consumer awareness around nutrition grows (Sandoval et al., 2020). However, opposing trends can emerge if consumer preferences prioritize processed, high-calorie foods, contributing to dietary imbalances, obesity, and non-communicable diseases (Amorim et al., 2022). These preferences may reduce access to nutritious options, especially for low-income groups, further undermining food security and perpetuating health disparities (Jacob et al., 2023). Marketing and advertising also play a crucial role, as campaigns promoting unhealthy food products may contribute to poor nutrition and reduce agency, limiting consumers' ability to make informed food choices (Kumar et al., 2020; Arnolds, 2023).

In the long term, social and cultural factors shape consumer behaviour, directly influencing sustainability and stability. Growing consumer awareness of health and nutrition encourages dietary shifts toward sustainable food practices, such as plant-based diets, which promote long-term food sustainability by reducing the environmental impact of food production (Randall et al., 2024; Schurr, 2020). However, urbanization and cultural shifts towards more globalized diets can negatively affect traditional food systems, reducing local food availability and creating reliance on imported or processed foods (Crush & Tawodzera, 2017). Education and awareness programs, on the other hand, can empower individuals to make healthier and more sustainable food choices, promoting better utilization and agency while supporting long-term sustainability (Mancini et al., 2017; Arnalte-Mul et al., 2020). Thus, consumer preferences and food choices, driven by a complex interplay of economic, cultural, and marketing factors, will continue to shape the food security landscape positively and negatively.

Food Waste Through Consumption

In the short term, excess food buying contributes to food waste, negatively impacting food availability. Consumers often buy more food than necessary due to promotional incentives, bulk discounts, and impulse purchases, which leads to the depletion of natural resources and a reduction in the amount of food available for consumption (Balan et al., 2022; Irani & Sharif, 2016; EC, 2023c). Additionally, confusion over food labels, particularly "best before" and "use by" dates, causes consumers to discard edible food prematurely, further reducing availability and access (Kavanaugh & Quinlan, 2020; Bertolozzi-Caredio et al., 2023). Inadequate in-home storage also exacerbates food waste as improper refrigeration or storage conditions lead to spoilage of perishable goods, diminishing food utilization and sustainability (Tomaszewska et al., 2022; Balan et al., 2022). This wastage increases food prices by driving demand for more food production, mainly affecting vulnerable populations who struggle to afford nutritious food, compromising access and equity (EC, 2023c).

In the long term, cultural attitudes towards food waste play a critical role in shaping sustainability and stability within food systems. Cultural norms that promote overconsumption and food waste, particularly in wealthier and food-secure households, threaten long-term food availability by wasting valuable resources that could be used to support food-insecure populations (Balan et al., 2022; Irani & Sharif, 2016). As food waste contributes to environmental degradation, including increased greenhouse gas emissions from decomposing food in landfills, it undermines the sustainability of food production systems. It aggravates the challenges posed by climate change (EC, 2023c). Moreover, reliance on larger package sizes and portioning strategies designed to reduce unit costs often results in consumers purchasing more food than they can, leading to further waste and negatively impacting sustainability (Balan et al., 2022; Wohner et al., 2019). Addressing food waste through improved packaging, better consumer education on portion sizes, and more precise labelling can positively impact all pillars of food security by reducing resource depletion, lowering food prices, and promoting sustainable consumption practices (Irani & Sharif, 2016; Tomaszewska et al., 2022). Ultimately, tackling food waste at the consumption stage is essential for enhancing long-term food security and ensuring equitable access to resources for all populations.

4.3 Interlinks, Interrelations and Trade-offs

Figure 4 (see next page) depicts the interlinks and interconnections among food security drivers (straight lines connecting two drivers).

Biophysical and Environmental

Biophysical and environmental factors are foundational to food security, as they directly influence the productivity of agricultural systems, the availability of natural resources, and the sustainability of ecosystems that support food production (Islam & Wong, 2017; Firdaus et al., 2020). Climate change is perhaps the most critical driver in this category, as shifts in global temperatures, precipitation patterns, and the frequency of extreme weather events (e.g., droughts, floods, and hurricanes) pose direct threats to agricultural productivity (Chen et al., 2020). These environmental shifts reduce crop yields and destabilize the delicate balance of ecosystems, exacerbating the spread of invasive species, pests, and diseases that further undermine food security (El Samra, 2017; Firdaus et al., 2020). Rising temperatures and altered rainfall patterns degrade soil health through erosion, salinization, and nutrient depletion, reducing the fertility of agricultural lands and limiting their capacity to produce food (Pimentel, 2006; Silatsa & Kebede, 2023; FAO, 2018).

The loss of biodiversity further compounds these challenges. As ecosystems lose species diversity, particularly among pollinators and other organisms essential to agricultural systems, the resilience of food production systems diminishes (Frison et al., 2011; Fedotova et al., 2021). Pollinators like bees, crucial for pollinating many crops, face population declines due to habitat destruction, pesticide use, and climate change, directly impacting food availability (Thrupp, 2000; Frison et al., 2011). Biodiversity loss also fosters the spread of pests and diseases, as natural pest control mechanisms are disrupted (Fedotova et al., 2021). This interconnection between biodiversity, climate, and food security illustrates the intricate feedback loops that can either stabilize or destabilize food systems (Thrupp, 2000; Fedotova et al., 2021).

Environmental pollution, especially air and water pollution, further complicates this web of interdependencies. Industrial agricultural practices, which rely heavily on chemical inputs like fertilizers and pesticides, contribute to the degradation of air, water, and soil quality (Sun, Dai, & Yu, 2017; Xia et al., 2023). Nitrogen runoff from agricultural lands contaminates water bodies, causing algal blooms that deplete oxygen and kill aquatic life, which impacts food sources derived from fisheries (Garcia & Rosenberg, 2010; Lancker, Fricke, & Schmidt, 2019). Similarly, greenhouse gas emissions contribute to climate change through air pollution, exacerbating the environmental stresses that threaten food security (Tai et al., 2014; Sun et al., 2017; Van Ingenen et al., 2009).

The trade-offs involved in addressing these biophysical and environmental drivers are significant. On the one hand, transitioning to more sustainable agricultural practices, such as conservation agriculture, agroforestry, and organic farming, can help mitigate environmental degradation and enhance ecosystem resilience (Wezel et al., 2014; Giller et al., 2009; Cárceles Rodríguez et al., 2022). However, these practices often come with higher costs, lower initial yields, and require land-use changes that may conflict with other economic priorities (Thomas et al., 2009; HLPE, 2013; Koizumi, 2015; Naylor & Higgins, 2018). Moreover, while technological innovations (such as drought-resistant crop varieties) can improve food security, they may also require significant investments that are not accessible to all regions, particularly in developing countries (Ogundari, 2014; Marambe et al., 2020). The challenge lies in balancing the need for increased food production with the imperative to preserve environmental health and biodiversity, both essential for long-term food security (Vira et al., 2015; Expósito, 2023).

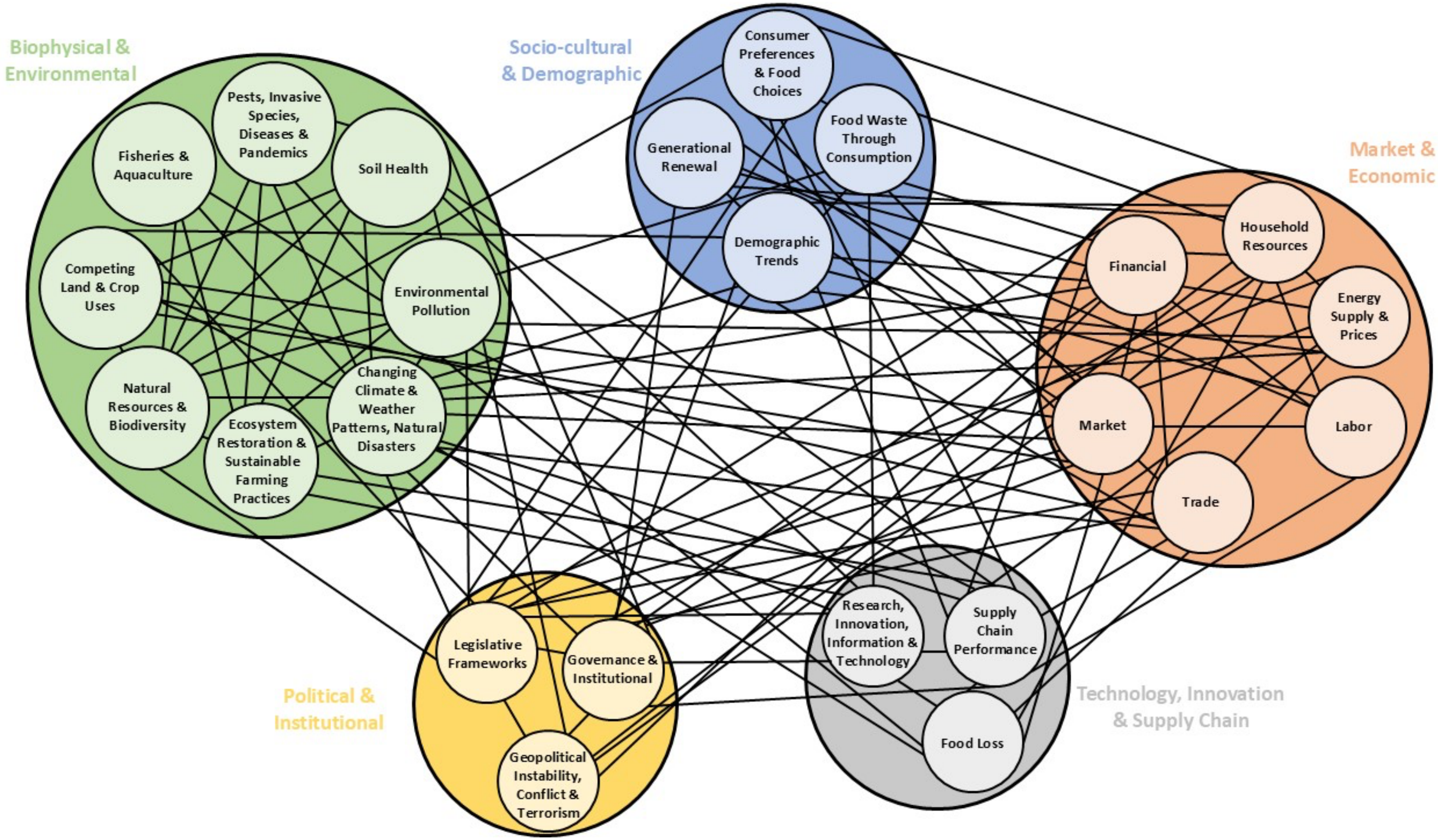

Figure 4 – Interlinks and interconnections of food security drivers

Technology, Innovation, and Supply Chain

Technology and innovation are critical enablers of food security, influencing everything from agricultural productivity to supply chain efficiency and food distribution. Technological advancements have revolutionized agricultural practices through innovations such as precision farming, biotechnology, and advanced irrigation systems, which help optimize the use of natural resources and increase crop yields (Wassmann et al., 2019; Manikas et al., 2022). Precision farming, for example, allows farmers to apply water, fertilizers, and pesticides more efficiently using data from sensors, satellites, and drones. This reduces waste, lowers production costs, and minimizes the environmental impact of farming, thus addressing both the productivity and sustainability challenges in food systems (Wassmann et al., 2019; Wudil et al., 2022; Munialo et al., 2024).

Innovations in biotechnology, such as the development of genetically modified crops, have also contributed to food security by enhancing crop resilience to pests, diseases, and environmental stresses like drought and salinity. These biotechnological advancements help stabilize food supplies in regions prone to climatic variability, where traditional crops may no longer thrive. However, adopting these technologies is often contentious, as concerns about the long-term environmental and health impacts of genetically modified organisms persist. The trade-offs here involve balancing the immediate benefits of increased food production with potential ecological risks and public resistance (EC, 2023c).

Supply chain innovation plays an equally critical role in food security. Efficient supply chains ensure that food moves smoothly from production to consumption, minimizing losses due to spoilage, waste, and logistical inefficiencies (Keating, 2013; Svanidze et al., 2019). Technological innovations, such as blockchain and IoT technologies, have improved supply chain traceability, enabling better tracking of food products throughout the supply chain. This enhances food safety, reduces contamination risk, and allows quicker responses to foodborne illness outbreaks (Nastasijević et al., 2017; Volz et al., 2020). Moreover, supply chain innovations contribute to reducing food waste, a significant issue in developed and developing countries. Approximately one-third of all food produced globally is lost or wasted, with much of this occurring during post-harvest handling, transportation, and storage. Addressing these inefficiencies through improved supply chain management can significantly enhance food availability and affordability (Kovaleva et al., 2022; Polukhin et al., 2021).

However, the benefits of technology and innovation are not evenly distributed across regions and socioeconomic groups. In many developing countries, smallholder farmers (a significant portion of the agricultural workforce) lack access to modern technologies and infrastructure. This digital divide creates productivity, income, and food security disparities between developed and developing regions (Premanandh, 2011; Warsame et al., 2022). Moreover, while supply chain improvements can reduce food loss, they require significant infrastructure, technology, and training investments. These investments may not be feasible for countries with limited financial resources, leading to trade-offs between short-term food security needs and long-term infrastructure development (Canali et al., 2017; Magalhães, Ferreira, & Silva, 2021; Das et al., 2023).

Additionally, the reliance on high-tech solutions in agriculture, such as automated farming equipment and AI-driven decision-making tools, raises concerns about the displacement of agricultural labour, particularly in regions where farming provides livelihoods for large portions of the population (EC, 2023c). As agricultural systems become more mechanized and less reliant on manual labour, there is a risk of exacerbating unemployment and social inequalities, which could undermine food security by reducing household incomes and access to food

(Burchi & De Muro, 2016; Martin, 2020). Therefore, while technology and innovation are key drivers of food security, they must be implemented in inclusive and equitable ways, ensuring that the benefits are shared across all levels of society (Bertolozzi-Caredio et al., 2023; FSA, 2023).

Market and Economic

Market dynamics and economic factors are central to the functioning of food systems, influencing everything from food production and distribution to pricing and accessibility. The global food market is shaped by a complex interplay of supply and demand, with fluctuations in these forces directly impacting food prices and food security (Sage, 2013; Zulfiqar, 2017). Economic drivers such as energy prices, labour costs, and trade policies all play a role in determining the affordability and availability of food (EC, 2023c). For example, rising energy costs increase the cost of agricultural inputs like fertilizers, fuel for machinery, and transportation, which drives up food prices. These price increases can devastate food security, particularly in low-income countries where a significant portion of household income is spent on food (Taghizadeh-Hesary et al., 2019; Hasegawa et al., 2020).

Globalization has increased the interconnectivity of food markets, allowing countries to import food during periods of domestic shortfall. However, this reliance on global markets also creates vulnerabilities, as disruptions in international trade (whether due to climate events, political instability, or economic sanctions) can lead to food shortages and price volatility (Sage, 2013; El Samra, 2017). For instance, during the COVID-19 pandemic, global supply chains were severely disrupted, leading to shortages of certain food items and price spikes in many countries. Similarly, geopolitical conflicts, such as the ongoing war in Ukraine, have disrupted the export of critical food commodities like wheat and sunflower oil, further exacerbating global food insecurity (Zulfiqar, 2017; Peyton et al., 2015).

Financial systems are also crucial in supporting agricultural production and food security. Access to credit, insurance, and investment capital allows farmers to purchase inputs, expand their operations, and recover from crop losses due to climate events (Millimet et al., 2018; Chang et al., 2014). However, financial markets are susceptible to external shocks, and volatility in global commodity markets can create risks for farmers and consumers alike (Pasqualino et al., 2019; Staugaitis & Vaznonis, 2022). For example, when global commodity prices rise, the cost of food increases, disproportionately affecting low-income households. In regions where financial systems are underdeveloped, farmers may struggle to access the capital needed to invest in productivity-enhancing technologies, leading to persistent food insecurity (EC, 2023c).

The economic trade-offs involved in addressing food security are significant. On the one hand, policies that promote free trade and market liberalization can enhance food availability by allowing countries to import food at lower costs (Bonuedi et al., 2020; Van Berkum, 2021). On the other hand, these policies can also undermine local agricultural industries, leading to increased reliance on food imports and reduced food sovereignty (McCorriston et al., 2013; Sun & Zhang, 2021). Similarly, while subsidies and price controls can make food more affordable for consumers, they can also distort market signals and reduce incentives for farmers to produce certain crops, leading to inefficiencies in food production and distribution (Ibrahim et al., 2023; Barros & Martínez-Zarzoso, 2022).

Furthermore, income inequality and poverty remain significant barriers to food security. Even in countries where food is abundant, economic disparities can prevent vulnerable populations from accessing adequate nutrition. Food deserts, where affordable and nutritious food is scarce, disproportionately affect low-income communities, particularly in urban areas. Addressing these economic drivers requires a multifaceted approach that includes social safety nets, targeted subsidies, and policies that promote inclusive economic growth. However, the challenge lies in balancing these interventions with market-based approaches that ensure the efficient allocation of resources and the long-term sustainability of food systems (EC, 2023c).

Political and Institutional

Political and institutional drivers profoundly impact food security by formulating and implementing policies, regulations, and governance structures. Governments play a critical role in shaping the agricultural landscape by enacting policies that regulate land use, water management, trade, and environmental conservation (Qureshi & Hanjra, 2015; Miewald et al., 2013). These policies influence how food is produced, distributed, and consumed, and they are essential for ensuring that food systems are resilient to internal and external shocks (Lusk et al., 2011; Black et al., 2012).

One of the most significant political drivers of food security is trade policy. International trade agreements determine the flow of food commodities across borders, affecting food availability and prices (Wahbeh et al., 2022; Sundaram, 2023). Trade policies such as tariffs, quotas, and subsidies can either enhance or hinder food security, depending on how they are designed and implemented. For example, protectionist policies that restrict food imports may benefit domestic producers in the short term, but they can also lead to higher food prices and reduced availability for consumers (Pavleska & Kerr, 2020). Conversely, trade liberalization can lower food prices and increase access to a wider variety of foods. Still, it can also expose domestic producers to competition from cheaper imports, potentially undermining local food production (Moosavi & Hosseini, 2021).

Institutional frameworks are equally crucial in managing food security. Effective governance ensures policies are implemented coherently, and resources are allocated efficiently. Strong institutions are needed to coordinate disaster response efforts, manage food reserves, and enforce social safety nets for vulnerable populations (Candel, 2018; Amjath-Babu & Krupnik, 2023). Food security is often compromised in regions with weak political and institutional capacity. For example, in conflict-affected areas, government institutions may be unable to provide essential services, leading to disruptions in food production and distribution (Belesky, 2014; Maystadt et al., 2014). Similarly, corruption and mismanagement in countries with weak governance can prevent food aid from reaching those who need it most, exacerbating hunger and malnutrition (Zimmermann et al., 2018; Krishnamurthy, 2020).

Political stability is another critical factor in maintaining food security. Political unrest, conflicts, and terrorism can disrupt food systems by damaging infrastructure, displacing populations, and limiting access to food markets (De Laurentiis & Sala, 2016; Abis & Demurtas, 2023). For example, the Syrian civil war has had devastating effects on food security, as agricultural production has been severely disrupted, and millions of people have been displaced from their homes (El-Jafari & Abu-Kwaik, 2019). Political instability also makes it difficult for governments to implement long-term food security strategies, as short-term crises take precedence over planning for the future (Minten & Stifel, 2023; George & Adelaja, 2022).

There are significant trade-offs involved in political and institutional approaches to food security. On the one hand, governments must balance the need to provide immediate relief to those facing food insecurity with the long-term goal of building resilient food systems (Bindraban et al., 2012; Amjath-Babu & Krupnik, 2023). This often requires difficult decisions about resource allocation, as investments in infrastructure, education, and health must compete with funding for food aid and subsidies (Qureshi & Hanjra, 2015). Additionally, while international trade can enhance food availability, it can also increase vulnerability to global market fluctuations, particularly for countries that rely heavily on food imports (Sundram, 2023; Lusk et al., 2011). Therefore, political and institutional efforts to address food security must strike a balance between fostering local agricultural production, promoting fair and open trade, and ensuring that social safety nets are in place to protect the most vulnerable populations (Moosavi & Hosseini, 2021; Miewald et al., 2013).

Socio-cultural and Demographic

Socio-cultural and demographic factors are pivotal in shaping food security outcomes by influencing consumption patterns, dietary preferences, labour availability, and population growth. These drivers are deeply intertwined with other dimensions of food security, such as economic, environmental, and political factors, creating complex feedback loops that affect food availability, accessibility, and utilization (EC, 2023c).

Demographic changes, particularly population growth and urbanization, are among the most significant drivers of food demand. As the global population continues to rise, particularly in developing regions, the demand for food is expected to increase dramatically (Duda et al., 2018; Tekwa, 2022). This growth places immense pressure on agricultural systems to produce more food, often leading to the intensification of farming practices, which can have detrimental effects on soil health, biodiversity, and water resources (Obi & Awoke, 2020; Kousar, Malik, & Shahbaz, 2021). Urbanization further complicates this dynamic, as the migration of people from rural to urban areas increases the demand for food in cities while reducing the availability of labour for agricultural activities in rural areas (Crush & Tawodzera, 2017; Hammelman, 2018). This shift also alters dietary patterns, as urban populations tend to consume more processed foods, meats, and dairy products, which require more resources to produce than traditional plant-based diets (Keswani, 2021; Grauel & Chambers, 2023).

Cultural factors also play a crucial role in shaping food preferences and consumption patterns. Dietary habits are often deeply rooted in cultural traditions, religious practices, and societal norms, which can influence the foods produced and consumed (Arrona-Cardoza, Bastida, & Alcántara, 2023; Arnolds, 2023). For example, in many parts of Asia, rice is a staple food, while maize or wheat may dominate diets in the Americas. These cultural preferences shape agricultural practices and food markets as farmers and producers respond to consumer demand (Regmi & Gehlhar, 2001; Kumar, Singh, & Prasad, 2020). However, cultural preferences can also create challenges for food security, particularly when they conflict with environmental sustainability. For instance, the growing global demand for meat, particularly in emerging economies, is placing increased pressure on land and water resources, as livestock farming is far more resource-intensive than crop production (Schurr, 2020; Amorim, Rocha & Fonseca, 2022).

Demographic trends also influence labour availability in agriculture. In many developing countries, young people are increasingly moving away from rural areas in search of better economic opportunities in cities, leading to a phenomenon known as rural depopulation (Żmija, Stec, & Michalik, 2020; Skrzypczyński, Majchrowska, & Wisniewski, 2021). This migration reduces the availability of labour for agricultural activities, which can hinder food production and contribute to food insecurity. At the same time, aging populations in many developed countries are creating labour shortages in the agricultural sector, as fewer young people are willing to take up farming as a profession (Mahon, 2012; Eistrup, Nordström, & Østergaard, 2019). These demographic shifts highlight the need for policies encouraging generational renewal in agriculture, such as providing incentives for young people to enter the sector and supporting smallholder farmers (Micha et al., 2019; Loring & Gerlach, 2015).

The trade-offs in addressing food security's socio-cultural and demographic drivers are complex. On one hand, promoting agricultural intensification and urbanization can boost economic growth and improve food availability in the short term. However, these strategies often come at the expense of environmental sustainability and social equity. For example, expanding industrial agriculture to meet growing food demand can lead to deforestation, soil degradation, and water scarcity, undermining the long-term resilience of food systems. Similarly, while urbanization can create new economic opportunities, it can also exacerbate inequalities in food access, as low-income urban populations often face higher food prices and limited access to nutritious foods (EC, 2023c). Therefore, addressing food security's socio-cultural and demographic drivers requires a balanced approach that promotes sustainable agricultural practices, equitable food distribution, and policies supporting rural and urban livelihoods.

4.4 Mapping with Target Interventions

Food security is a critical global challenge, affecting millions and involving complex environmental, economic, political, and social issues. Addressing this requires targeted responses that account for the diverse, interconnected drivers influencing food security. Key drivers, including climate change, economic instability, conflict, and urbanization, impact food systems differently based on context. Understanding these drivers, their interconnections, and trade-offs is essential for crafting effective solutions. Following comprehensive analysis, we have identified a list of targeted interventions to address these challenges. Interventions such as climate-smart agriculture, economic empowerment programs, and peacebuilding efforts are tailored to specific drivers and community needs. By creating resilient food systems that can adapt to immediate and long-term pressures, these strategies aim to build sustainable food security solutions capable of withstanding evolving global challenges. These interventions contribute to a more secure, equitable food system for vulnerable populations (Table 3).

Table 3 – Target interventions to stimulate food security drivers to increase the resilience of food systems.

<table>
<tr><th>Intervention</th><th>References</th></tr>
<tr><td>Climate change mitigation policies (e.g., climate-resilient crop varieties, early warning systems, etc.)</td><td>Desta & Coppock, 2002; Nkedianye et al., 2011; Yadav et al., 2015; Islam & Wong, 2017; IPCC, 2019; EC, 2022b; 2023d; Bertolozzi-Caredio et al., 2023; Galanakis, 2023; Hobbins et al., 2023</td></tr>
<tr><td colspan="2">Climate change exacerbates food insecurity through unpredictable weather patterns, increased frequency of extreme events, and shifting growing conditions. Drivers such as rising temperatures, altered rainfall, and natural disasters directly reduce agricultural productivity, affecting food availability. Climate-resilient crop varieties can be developed to mitigate these impacts, helping crops withstand these changes. Early warning systems further help by providing advance notice of extreme weather events, allowing farmers to prepare. Moreover, irrigation systems designed for water conservation and reforestation efforts contribute to stabilizing food systems. Effective climate change mitigation can preserve agricultural productivity and protect food systems' availability, access, and stability.</td></tr>
<tr><td>Pollution prevention policies (e.g., managing emissions, carbon reduction, sustainable waste management, etc.)</td><td>Lu et al., 2015; Köninger et al., 2021; Steenkamp et al., 2021; EC, 2023d; Bertolozzi-Caredio et al., 2023; Galanakis, 2023; Irfeey et al., 2023</td></tr>
<tr><td colspan="2">Environmental pollution, including air, water, and soil, degrades agricultural land and ecosystems, reducing food productivity. Pollution also introduces toxins into the food chain, impacting food utilization and health. Target interventions like pollution management policies, lowering emissions, and promoting sustainable waste management practices will reduce these harmful effects. For instance, reducing industrial waste and using cleaner technologies can maintain soil health, safeguard water resources, and improve crop yield. Addressing pollution at its source helps stabilize food supply chains, ensuring clean, safe food and preventing ecosystem degradation, which threatens long-term sustainability and availability.</td></tr>
<tr><td>Soil restoration initiatives (e.g., reforestation, conservation tillage, cover cropping, etc.)</td><td>EC, 2022b; 2023d; Bertolozzi-Caredio et al., 2023; Haughey et al., 2023</td></tr>
<tr><td colspan="2">Soil erosion, nutrient depletion, and contamination are significant drivers of food insecurity, as they diminish the land's ability to support agriculture. Initiatives such as reforestation, conservation tillage, and cover cropping can restore degraded soils and improve their fertility. These methods also enhance water retention and prevent further erosion, contributing to the sustainability of food systems. Soil restoration ensures that agricultural lands remain productive, supporting long-term food availability and access while reducing the environmental impact of food production. Healthier soils also improve the nutritional value of crops, positively influencing food utilization.</td></tr>
<tr><td>Biodiversity preservation practices (e.g., habitat restoration, pollinator-friendly landscaping practices, etc.)</td><td>Yadav et al., 2015; van der Sluijs & Vaage, 2016; EC, 2022b; 2023d; Bertolozzi-Caredio et al., 2023</td></tr>
<tr><td colspan="2">The decline in biodiversity affects food security by reducing ecosystem services essential for agriculture, such as pollination and natural pest control. Habitat restoration and pollinator-friendly landscaping practices are crucial for maintaining biodiversity and supporting stable and resilient agricultural systems. For example, restoring pollinator habitats ensures better crop yields while maintaining a variety of species within agricultural ecosystems promotes natural resilience against pests. Protecting biodiversity also ensures the long-term sustainability of food production, as diverse ecosystems are better equipped to cope with environmental stressors.</td></tr>
</table>

Sustainable pest management practices (e.g., biological control, integrated approaches, crop rotation, etc.)	Popp et al., 2013; Yadav et al., 2015; Mahmood et al., 2016; EC, 2023d
Pests and diseases threaten crop and livestock production, reducing food availability and affecting market stability. Traditional chemical pesticides can exacerbate environmental degradation, so sustainable pest management practices are critical. Biological control, integrated pest management (IPM), and crop rotation reduce dependence on chemical pesticides, promoting long-term sustainability. By encouraging natural predators and ecological balance, these practices help maintain healthy agricultural ecosystems, ensuring stable food production and reducing environmental harm, thus positively impacting food availability, access, and utilization.	
Sustainable farming practices (e.g., organic farming, soil carbon sequestration, etc.)	Giller et al., 2009; Wezel et al., 2014; Köninger et al., 2021; Steenkamp et al., 2021; Cárceles Rodríguez et al., 2022; EC, 2022b; 2023d; Bertolozzi-Caredio et al., 2023; Haughey et al., 2023
Unsustainable farming practices, such as overuse of chemical inputs, degrade soil and water resources, contributing to long-term food insecurity. Sustainable farming practices, such as organic farming and soil carbon sequestration, enhance the resilience of food systems. Organic farming reduces dependency on synthetic inputs, improving soil health and water quality, while soil carbon sequestration helps mitigate climate change. These methods promote the long-term availability of food and preserve environmental resources, ensuring that food systems remain productive and sustainable for future generations.	
Updated common agricultural and fisheries policies mechanisms (e.g., measures to reduce mediators from farm to fork, sustainable fishers' management plants, etc.)	Chepeliev et al., 2023; EC, 2023d
Agricultural and fisheries policies prioritizing sustainability and reducing supply chain inefficiencies are essential for maintaining stable food supplies. Reducing intermediaries between farmers and consumers, promoting sustainable fisheries management, and ensuring equitable resource access are critical interventions. These policies can prevent overfishing and depletion of marine resources, ensuring that food from these sectors remains available and affordable. Sustainable management of fisheries and agriculture supports food availability, access, and stability while safeguarding the long-term health of ecosystems.	
Promoting practices to restore fisheries and aquaculture (e.g., marine protected areas, integrated multitrophic aquaculture, etc.)	Garcia & Rosenberg, 2010; Lancker et al., 2019
Overfishing and habitat destruction threaten the availability of fish, a critical protein source for many populations. Marine protected areas, integrated multitrophic aquaculture, and sustainable management practices are essential for restoring fish stocks and maintaining biodiversity. These interventions help balance the demand for seafood with the need to protect marine environments, ensuring the long-term sustainability of fisheries. Promoting practices that restore depleted fisheries, food availability, and stability are preserved, benefiting coastal communities and global food markets.	
Promoting sustainable land use management (e.g., land use planning and zoning, considering both food and biofuel production, etc.)	Blaikie & Brookfield, 1987; Bindraban et al., 2012; Steenkamp et al., 2021; EC, 2022b; Yu & Deng, 2022; Haughey et al., 2023
Competition for land between food production, biofuels, and urbanization puts pressure on agricultural systems. Sustainable land use planning and zoning that prioritize food production can help mitigate these pressures. Land use strategies that account for both food and biofuel production can balance these competing demands, ensuring that food availability is not compromised. Sustainable land use management also supports food systems' long-term stability and sustainability by protecting agricultural land from excessive development.	

More investment in research and innovation (e.g., institutional research, IT solutions, Industry 4.0 applications, automation, etc.)	Yadav et al., 2015; Bertolozzi-Caredio et al., 2023; Galanakis, 2023; EC, 2022b; 2023d
Technological innovation is crucial for addressing the drivers of food insecurity. Investment in agricultural research, IT solutions, and automation can increase agricultural productivity, reduce food loss, and make supply chains more resilient. For example, developing disease-resistant crop varieties and precision agriculture techniques can improve yields and reduce environmental impact. These innovations ensure that food systems are better equipped to meet growing global demands while preserving sustainability. Expanding research and innovation also helps build resilient food systems that adapt to future challenges.	
Promotion of shorter food supply chains (e.g., facilitation of platforms for direct sales, logistical support for small-scale producers to access local markets, etc.)	EC, 2018; Steenkamp et al., 2021; Galanakis, 2023
Long and inefficient food supply chains increase food waste and reduce the freshness and quality of food, negatively impacting food availability and utilization. Promoting shorter food supply chains, such as direct sales platforms and logistical support for small-scale producers, can help reduce these inefficiencies. Local markets are better served by facilitating closer connections between producers and consumers, reducing transportation costs and food loss during transit. This enhances food access by providing fresher products while stabilizing prices for consumers and producers alike. Shorter supply chains strengthen local economies, reduce environmental impacts, and contribute to more sustainable and resilient food systems.	
Facilitate improved traceability in the food supply chain (e.g., for advanced quality control, tracking of food contamination, etc.)	EC, 2022b; Bertolozzi-Caredio et al., 2023; Galanakis, 2023
Food safety and contamination are critical concerns for food security, particularly regarding utilization. Implementing advanced traceability systems allows for better tracking of food products from farm to fork, improving quality control and ensuring faster response to contamination events. Improved traceability enhances consumer confidence and reduces food loss due to recalls or safety concerns. It also helps maintain the stability and sustainability of supply chains by ensuring that food is safely transported, processed, and sold. Enhanced traceability is essential for safeguarding food utilization, protecting public health, and minimizing food waste.	
Facilitation strategies to reduce food loss (support cold chain infrastructure, provide better storage facilities, educate on proper handling, etc.)	IPCC, 2019; Steenkamp et al., 2021; EC, 2022b; 2023d; Galanakis, 2023
Food loss occurs at multiple supply chain stages, from production to post-harvest handling, storage, and distribution. Cold chain infrastructure, improved storage facilities, and education on proper food handling are critical interventions for reducing food loss. By supporting these strategies, food systems can minimize waste, ensuring more food reaches consumers in good condition. Reducing food loss enhances food availability, especially in regions where food insecurity is prevalent. It also contributes to the long-term sustainability of food systems by conserving resources and improving efficiency, ultimately stabilizing food markets and improving access.	
Exceptional EU financial support (e.g., emergency relief funds, low-interest loans to agricultural businesses, subsidies for insurance premiums, etc.)	EC, 2022b; Chepeliev et al., 2023
Economic instability, climate shocks, and other crises can disrupt food systems, making financial support critical for maintaining food security. Exceptional EU financial support in the form of emergency relief funds, low-interest loans, and subsidies for insurance premiums helps stabilize agricultural businesses during crises. These financial mechanisms ensure farmers can continue production despite adverse conditions, maintaining food availability and access. The EU can protect vulnerable agricultural sectors and enhance resilience by offering financial assistance, ensuring that food systems remain stable and sustainable even in challenging circumstances.	

Market interventions (e.g., price stabilization mechanisms, facilitating access to credit and financial instruments for small-scale producers, etc.)	EC, 2022b; Bertolozzi-Caredio et al., 2023; Galanakis, 2023
Price volatility, lack of access to credit, and market instability are significant drivers of food insecurity. Market interventions, such as price stabilization mechanisms, credit facilitation, and financial instruments for small-scale producers, can help mitigate these risks. Stabilizing prices ensures that food remains affordable for consumers while providing access to credit, which allows farmers to invest in productivity-enhancing technologies. Market interventions enhance food access and availability by supporting producers and consumers, ensuring that food systems remain resilient to external shocks and market fluctuations.	
Integration of renewable energy technologies (e.g., adoption through subsidies and tax credits, supportive regulatory frameworks to accelerate their integration, etc.)	IPCC, 2019; EC, 2022b
Energy costs significantly drive food production expenses, impacting food availability and sustainability. Integrating renewable energy technologies, such as solar and wind power, into agricultural and food processing systems can reduce these costs while minimizing environmental impact. Subsidies, tax credits for renewable energy adoption, and supportive regulatory frameworks can accelerate the transition to sustainable energy solutions. This intervention reduces the carbon footprint of food production, enhances food availability by lowering production costs, and contributes to the long-term sustainability of food systems by reducing reliance on fossil fuels.	
Unrestricted movement of commodities within the EU (e.g., streamline customs procedures, harmonize regulatory standards, enhance transportation networks, etc.)	EC, 2022b; Bertolozzi-Caredio et al., 2023; Chepeliev et al., 2023
Trade barriers and inefficient transportation networks hinder the movement of food commodities, creating shortages and price volatility. Streamlining customs procedures, harmonizing regulatory standards, and enhancing transportation networks can facilitate the free movement of food products within the EU. This ensures that food reaches markets efficiently, improving consumer availability and access across member states. The unrestricted movement of commodities helps stabilize food prices, reduces food waste during transit, and enhances the resilience of food systems by ensuring that supply chains remain fluid and responsive to demand.	
Adaptability in trade regulations (e.g., trade agreements with flexibility clauses, establish mechanisms for temporary tariff adjustments, offer trade incentives, etc.)	FAO, 2018; IPCC, 2019; EC, 2022b; Chepeliev et al., 2023
Global trade is crucial to food security, but rigid trade regulations can exacerbate food shortages and price fluctuations. Trade agreements with flexibility clauses, mechanisms for temporary tariff adjustments, and trade incentives can help mitigate these risks. By adapting trade regulations to accommodate changing market conditions, countries can ensure that food remains available and affordable, even during economic instability or geopolitical conflict. Flexible trade policies support food access and availability while enhancing the stability of global food systems, making them more resilient to external shocks.	
Supporting labour policies (e.g., incentives for labour mobility to regions experiencing labour shortages, laws to ensure fair wages, training programs to enhance labour skills, etc.)	EC, 2022b
Labor shortages in the agricultural sector threaten food production and stability, particularly in regions experiencing demographic shifts or economic migration. Incentives for labour mobility, fair wage laws, and training programs to enhance labour skills are critical interventions for maintaining a stable workforce. These policies ensure that food production remains consistent and that labour is available to support all stages of the food supply chain. By improving labour conditions and supporting mobility, agricultural systems can meet production demands, ensuring food systems' availability, access, and stability in the short and long term.	
Social protection and poverty reduction policies (e.g., provide financial assistance or subsidies to low-income households, promote income equality through policies, etc.)	EC, 2018; Steenkamp et al., 2021; EC, 2022b

Poverty is a crucial driver of food insecurity, as low-income households struggle to access adequate and nutritious food. Social protection measures, such as financial assistance, food vouchers, and subsidies for essential goods, can significantly improve food access for vulnerable populations. Policies promoting income equality, such as wage support and job creation programs, further enhance food security by increasing households' purchasing power. Social protection policies help stabilize food systems by ensuring that economic downturns or crises do not disproportionately affect low-income groups, thus contributing to food availability, access, and utilization.	
Favorable legislative framework and flexibility on rules in exceptional circumstances (e.g., subsidies, tax discounts, emergency waivers, etc.)	EC, 2022b; Bertolozzi-Caredio et al., 2023; Chepeliev et al., 2023; Galanakis, 2023
Food security is often threatened by rigid regulatory frameworks that cannot adapt to natural disasters, pandemics, or economic shocks. A legislative framework that includes flexibility in rules, such as subsidies, tax discounts, and emergency waivers, can ensure that food production and distribution continue uninterrupted during exceptional circumstances. By supporting farmers and businesses in times of crisis, these policies protect food availability and stabilize markets, ensuring that food systems remain resilient and capable of meeting demand during emergencies.	
Crisis response mechanisms (e.g., regularly updated plans at national and regional levels, rapid response teams, coordination among relevant agencies and stakeholders, etc.)	EC, 2022b; Galanakis, 2023
Food systems are highly vulnerable to climate disasters, pandemics, and geopolitical conflicts. Regularly updated national and regional crisis response plans, rapid response teams, and coordinated efforts among stakeholders are essential for minimizing food production and distribution disruptions. Crisis response mechanisms ensure that food remains available and accessible during emergencies while reducing the long-term impact of these events on food security. Effective crisis management contributes to the stability and sustainability of food systems, protecting vulnerable populations from food shortages and price spikes.	
National and international governance (e.g., transparent and accountable governance structures, fostering collaboration between governments and international organizations, etc.)	EC, 2022b; Galanakis, 2023
Governance structures are critical in managing food security by ensuring transparent and accountable decision-making. National and international collaboration, such as partnerships between governments, NGOs, and international organizations, helps create a coordinated approach to food security challenges. Strong governance structures enhance food system stability by promoting policies that support sustainable agriculture, equitable access to resources, and effective crisis management. International governance also facilitates cross-border collaboration in addressing global challenges like climate change, trade disruptions, and resource shortages, ensuring long-term sustainability and food security.	
Measures to tackle geopolitical instability, conflict, and terrorism (e.g., enhance diplomatic efforts, strengthen security measures, humanitarian aid to affected populations, etc.)	EC, 2022b
Geopolitical instability and conflict are significant drivers of food insecurity, as they disrupt food production, supply chains, and markets. Enhancing diplomatic efforts, strengthening security measures, and providing humanitarian aid to affected populations are essential to mitigating these impacts. Addressing the root causes of instability, such as resource scarcity and economic inequality, these measures help stabilize regions and ensure that food remains available and accessible. Humanitarian aid, in particular, ensures that vulnerable populations receive food during crises, supporting food availability, access, and stability.	
Community engagement (e.g., initiatives to promote local food production and distribution, workshops on sustainable farming practices, promotion of urban farming, etc.)	EC, 2018; Steenkamp et al., 2021; Galanakis, 2023

Local food production and distribution are critical to food security, particularly in crisis or market instability. Community engagement initiatives (such as promoting urban farming, organizing workshops on sustainable farming practices, and supporting local food distribution networks) empower communities to take control of their food security. These initiatives strengthen local economies, improve food access, and promote resilience by reducing dependency on long supply chains. By fostering community engagement, food systems become more responsive to local needs, enhancing availability, access, and stability.	
Measures to align with the demographic trends (e.g., policies for urbanization challenges, support aging populations in rural areas, manage migration flows, etc.)	Yadav et al., 2015
Demographic shifts, such as urbanization, population aging, and migration, significantly impact food systems. Policies that address these trends, such as urban planning that supports local food markets and programs that support aging rural populations, are essential for maintaining food security. By aligning food systems with demographic realities, these policies ensure that food remains available and accessible to all populations. Managing migration flows and supporting labour mobility also contribute to stable food production and distribution, ensuring that food systems can meet changing demand patterns.	
Policies for generational renewal (e.g., mentorship programs to transfer agricultural knowledge from older to younger ones, grants for young farmers to access land and resources for agricultural production, etc.)	DG AGRI, 2019; ENRD, 2020
The agricultural sector faces a generational gap, as younger generations are often discouraged from pursuing farming due to a lack of access to land, resources, and financial support. Policies that promote generational renewal, such as mentorship programs, grants for young farmers, and access to affordable land and credit, are critical for ensuring the sustainability of food systems. These interventions empower the next generation of farmers to adopt sustainable practices and innovate, ensuring that agricultural productivity remains high and that food systems are resilient to future challenges.	
Measures to guide consumer preferences and food choices (e.g., education for sustainable food choices, food labelling initiatives, campaigns for local and seasonal food markets, etc.)	Steenkamp et al., 2021
Consumer preferences significantly impact food systems, influencing demand for certain products and driving agricultural practices. Education on sustainable food choices, labelling initiatives, and campaigns promoting local and seasonal food markets can guide consumers toward more sustainable diets. These interventions help reduce the environmental impact of food production, improve food utilization, and ensure that local food systems remain vibrant. By encouraging consumers to make informed choices, food systems become more sustainable, contributing to long-term food availability and stability.	
Food waste reduction measures (e.g., public awareness campaigns, collaboration with retailers to implement portion control measures, reducing oversized packaging, etc.)	EC, 2022b; Galanakis, 2023
Food waste at the consumer level significantly reduces food availability and exacerbates environmental degradation. Public awareness campaigns, collaborations with retailers to reduce portion sizes, and improved packaging solutions can help reduce food waste. By addressing food waste, food systems become more efficient, ensuring that more food reaches consumers and reducing the environmental footprint of food production. These measures enhance food availability, stabilize markets, and promote sustainability by minimizing waste and conserving resources.	

5 Drivers' Validation and Zoom-in the Case Studies

5.1 EU Survey Questionnaires' Results

A structured EU-wide survey has been developed to capture stakeholder insights using a combination of multiple-choice and Likert-scale questions, organized into sections focusing on demographic information, risk categories (e.g., biophysical, economic or supply chain), intervention preferences, and organizational strategies for food security and resilience management (Annex A includes all the questions of the EU survey).

Initially, participants were selected using a purposive sampling to ensure representation across critical sectors, including agriculture, processing, distribution, and policymaking. The responders were asked to identify their type (e.g., private entity, NGO, authority), food sector (e.g., grains, fruits, dairy, seafood), role in the supply chain (e.g., processing, logistics, retail), country of operation and geographic scope (single country, EU-wide, or global), organization size (micro to large), as well as whether they engage in commodity exports within or outside Europe. After that, responders were asked to prioritize the six food security pillars (availability, access, utilization, stability, agency, and sustainability) based on their perceived importance. Rankings were assigned on a scale from 1 (most important) to 6 (least important). They were also asked to indicate those hazards and threats that have impacted in the past (historical incidents) the regular operation of the food sector they represent as well as their likelihood of affecting that sector in the short (next 3 years) and long term (by 2050).

Moreover, the respondents were asked to list those hazards and threats that, in case of occurrence, may have the highest impact on the operation of the food sector and the overall food security. These include biophysical and environmental factors (e.g., climate change, pollution, biodiversity loss, diseases, and pandemics), supply chain challenges (e.g., an inadequate performance due to disruptions in transport and logistics, cyber-attacks, technical risks, increased food loss due to storage conditions), economic volatility (e.g., due to price volatility, fluctuations in energy prices, market instability, trade, labour shortage), political instability (e.g., due to conflicts, war, and terrorism or due to lack of legislative frameworks and governance), and socio-cultural shifts (e.g., demographic trends, generational renewal, changes in consumer preferences). Respondents were also asked to prioritize the importance (on a 5-step scale of "not important" =1 to "very important" =5) of the 29 targeted interventions (Table 3) that could foster food systems' resilience against short- and long-term shocks and stresses. Additionally, the questionnaire explored responders' perspectives on whether organizations conduct risk assessments to anticipate disruptions, implement crisis preparedness measures (e.g., information sharing, early warnings), adopt long-term strategies (e.g., renewable energy, waste reduction), establish resilience plans, engage in governance for food security collaboration, report stock data for commodity monitoring, use digital tools for crisis communication, access platforms for monitoring food-related data (e.g., weather, markets) and receive early warnings to identify and address potential crises.

The EU survey has been disseminated between the EU and Associated Countries stakeholders, targeting participants from various sectors, including agriculture, processing, distribution, and policymaking. Fifty-three completed anonymous surveys were collected and analysed to determine response percentages. To calculate the Mean Score for each pillar, a reverse ranking system was applied: the highest rank (1) was assigned a score of 6, the second rank (2) a score of 5, and so on, down to a score of 1 for the lowest rank (6). The Mean Score was then calculated as the average of all assigned scores across n = 48 respondents (53 responses -5 no answers). The ±standard deviation was calculated to measure the variability of responses, reflecting consensus (or lack thereof) among stakeholders. The Mean Score of interventions (± standard deviation) was calculated from responses on a 1 to 5 scale, with sample sizes n = 47-50 per intervention. Pairwise comparisons were conducted using Tukey's Honest Significant Difference (HSD) test as a post hoc analysis following a one-way ANOVA to evaluate all pairs of means, determine statistical significance at the 5% level, and adjust the threshold to control the overall error rate across scores. Tukey's HSD test was chosen for its robustness in comparing group means while controlling for Type I error rates in multiple comparisons.

5.1.1 General Information of EU Survey Participants

Figure 5 presents the demographic profile of the respondents, detailing their type, organization status and size, export status, EU country of origin, food sector, and supply chain role. The EU survey captured diverse perspectives from stakeholders in the European food sector. Respondents included 41.5% private entities, 15.1% cooperatives or NGOs, 9.4% national or EU authorities, 5.7% international organizations, and 30.2% research institutions (Figure 5a). Key sectors represented included grains, dairy, seafood, meat, fruits, and vegetables, while 32.1% identified niche areas like viticulture and frozen foods. Regarding supply chain roles, 52.8% were involved in production, 28.3% in processing and packaging, and 22.6% in transport/logistics (Figure 1f). Wholesale, consumption, and retail were less represented (16.9%, 17.0%, and 15.1%, respectively), with 37.7% citing other roles (e.g., research and development or certification) (Figure 1g). Responses spanned European countries like Greece (24.5%), Finland (20.7%), and France (9.4%), while many (20.8%) respondents did not define their origin (Figure 1e). Most operated within a single country (43.4%), 39.6% had European and non-European activities, and 15.1% operated across Europe (Figure 5b). Large organizations led (49.1%), followed by medium (33.9%), micro (9.4%), and small entities (7.6%) (Figure 5c). Export activity varied, with 43.4% unaffected, 26.4% reporting no exports, and 28.3% exporting outside Europe (Figure 5d). The diverse stakeholder representation in this study aligns with Bertolozzi-Caredio et al. (2023), highlighting the importance of multi-stakeholder collaboration for comprehensive risk mapping and resilience strategies in the EU food supply chain.

Figure 5 – Demographic profile of the respondents: (a) Stakeholder types, (b) Organization status, (c) Organization size, (d) Export status, (e) EU Member States representation, (f) Food sector representation, and (g) Supply chain stages.

5.1.2 Hazards and Threats

The radar chart in Figure 2 highlights how organizations prioritize food security pillars to address hazards. "Availability" ranks highest, reflecting its critical role in ensuring a reliable, high-quality food supply across Europe. "Access," ranked second, underscores the importance of economic and physical means to obtain food, while "Sustainability," ranked third, emphasizes balancing production with environmental preservation and long-term goals. "Stability," fourth, depends on availability and sustainability to ensure consistent food system performance. In contrast, "Utilization" and "Agency" rank lower, suggesting immediate concerns like supply and access overshadow them. Standard deviations reveal strong consensus on the importance of availability and access, while broader variability for utilization and agency reflects diverse stakeholder perspectives. This prioritization provides insights into how organizations are navigating current food security challenges. The focus on availability, access, and sustainability aligns with the need to address immediate supply concerns while simultaneously building resilient systems for the future. The emphasis on 'availability' and 'access' suggests a pressing need to address immediate supply concerns, particularly in recent geopolitical and climatic disruptions (Kalkuhl et al., 2016). Lower prioritization of utilization and agency suggests areas that may require further advocacy and integration into broader food security strategies. Likewise, prioritizing availability and access as critical food security pillars aligns with the FAO (2006) framework, which emphasizes their foundational role in ensuring stable and equitable food systems, particularly in resource constraints and external shocks.

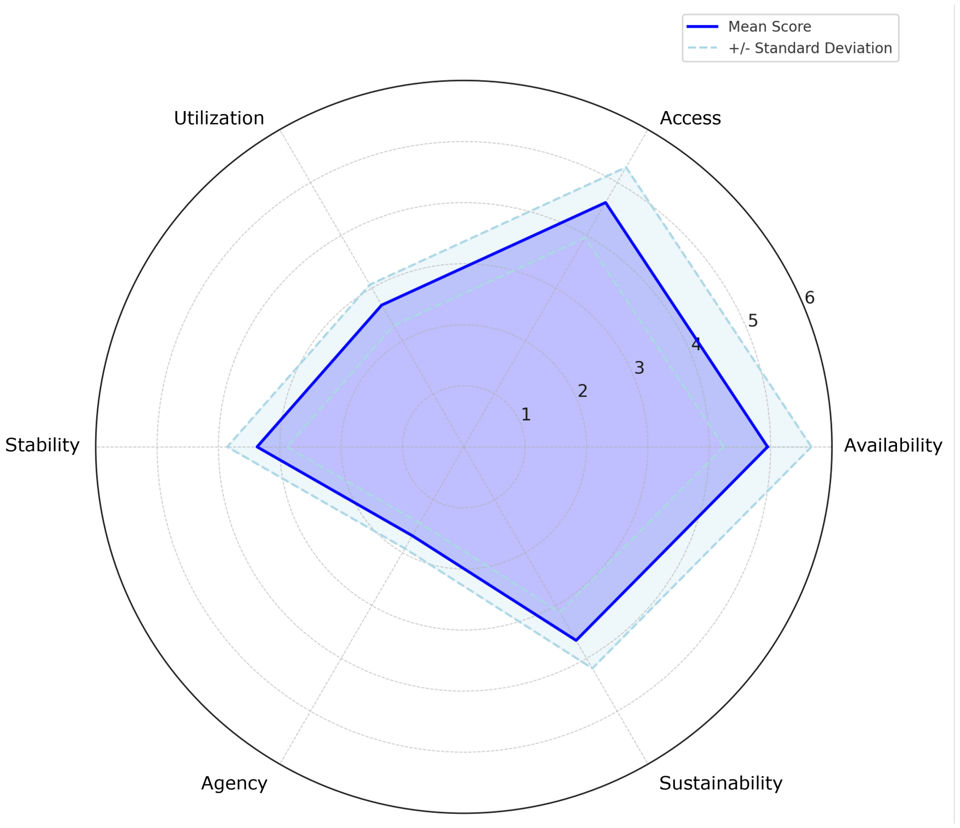

Figure 6 – Radar chart of Mean Score assigned to six food security pillars by stakeholders, with the data derived from an EU-wide survey (n = 48).
The blue line and filled area represent the mean scores for each pillar, highlighting their relative prioritization. Dashed light blue lines and the shaded area indicate the range of scores (mean ± standard deviation), reflecting the variability of stakeholder responses.

The survey explored hazards and threats affecting the food sector, focusing on the following categories: biophysical and environmental, supply chain, market, and economic, political and institutional, socio-cultural, and demographic risks. Respondents identified past impacts, their likelihood within three years and by 2050, and threats that, if they occur, could have the most significant impact on the operation of the food sector and overall food security. Results for biophysical and environmental risks (Figure 7) highlighted "changing climate and weather patterns" as the top biophysical and environmental concern, reflecting anticipated climate-related disruptions to food production and supply chains. "Pests, invasive species, diseases, and pandemics" ranked second, particularly for their current impacts, while "Environmental Pollution" was the third primary concern. Lesser-ranked issues like deterioration of soil health and natural resource degradation became important in long-term considerations. These findings indicate the critical challenges posed by climate change, biodiversity loss, and environmental health, emphasizing the need for strategic resilience and mitigation measures to secure the future of food systems. Besides, identifying climate-related disruptions and biodiversity loss as significant hazards aligns with the IPCC (2019) findings, which highlight that climate change exacerbates food security challenges by increasing the frequency and intensity of extreme weather events, contributing to land degradation, and reducing agricultural productivity in vulnerable regions.

When evaluating supply chain risks, “inadequate supply chain performance” has been highlighted as the most frequently cited hazard, reflecting persistent concerns about logistics, storage, and transportation reliability within the food sector. Although “food loss” was also acknowledged as an essential issue, it consistently ranked below supply chain performance concerns, indicating the need for robust logistical networks to minimize disruptions across the food supply chain. Many “no answer” responses were noted, suggesting that respondents may encounter unique supply chain challenges not captured in the survey options, highlighting the need for customizable, sector-specific strategies to boost supply chain resilience, emphasizing technological innovation like digitization and blockchain as transformative tools for improving traceability, reducing waste, and resolving logistical challenges (Aung & Chang, 2014). Moreover, the challenges in supply chain logistics and food loss align with Steenkamp et al. (2021) and Galanakis (2023), who emphasized the need for shorter, more localized supply chains and innovative interventions like urban agriculture to mitigate logistical inefficiencies, reduce food miles, and address urban food security risks.

For market and economic risks, Figure 7 identifies financial instability, including price volatility, as the top hazard across past, present, and future scenarios, highlighting the critical need for economic resilience within the food sector. Market instability and energy supply disruptions also emerged as significant concerns, with respondents viewing them as persistent threats to future food security. Additionally, “trade” risks and “labour shortages” are growing challenges, likely influenced by recent events such as the COVID-19 pandemic and geopolitical conflicts that have strained global supply chains and labour markets. These findings underscore the necessity of future resilience strategies that prioritize economic stability, workforce sustainability, and robust supply chain networks to secure food systems in an interconnected global market. Market volatility, driven by energy price fluctuations and geopolitical tensions, is a well-established food security risk, disproportionately affecting vulnerable populations and emphasizing the need for effective policy measures to stabilize markets and ensure equitable food access (Kalkuhl et al., 2016; Chepeliev et al., 2023).

Regarding political and institutional risks, “geopolitical instability” is perceived as an increasingly significant hazard, with respondents expecting a little decline in its short and long-term impact. This concern likely reflects the effects of ongoing global tensions and conflicts on food trade and supply chains. In contrast, “lack of legislative frameworks and governance” exhibits a decreasing trend, suggesting growing confidence in existing governance structures. However, a slight increase in governance concerns is noted for the long term, possibly due to uncertainty about the capacity of future regulations to address emerging challenges in the food sector. These findings highlight the importance of maintaining adaptable and forward-looking regulatory frameworks to navigate evolving global challenges and ensure food security effectively. The identification of geopolitical instability as a significant food security hazard aligns with Candel and Biesbroek (2018), who highlighted the need for enhanced policy integration and coherence across governance subsystems to address the cross-cutting challenges of global food security, particularly in the face of political disruptions and fragmented institutional frameworks.

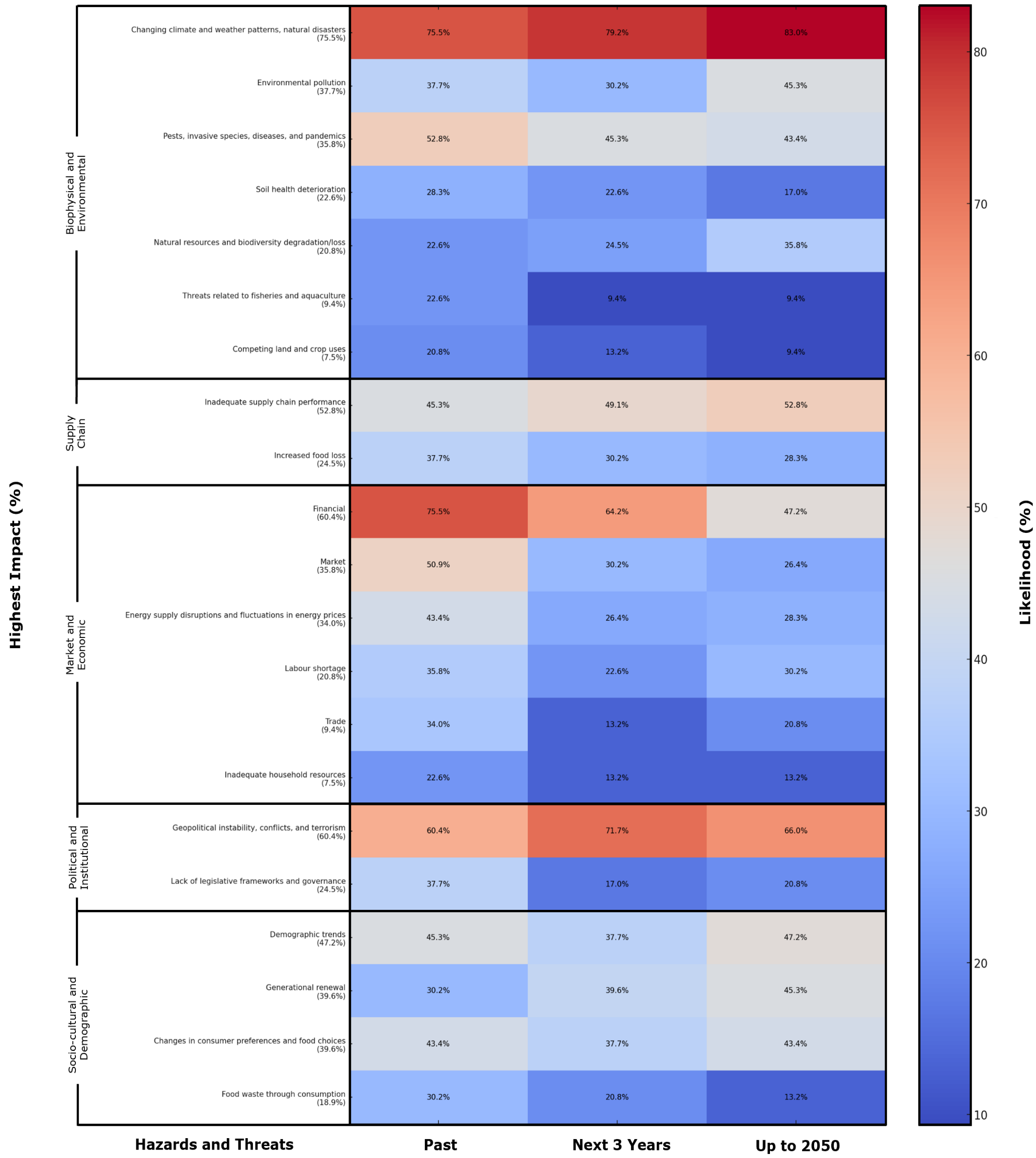

Figure 7 – Hazards and threats that have impacted the regular operation of the food sector in the past (historical incidents) as well as their likelihood of affecting that sector in the short (next 3 years) and long term (by 2050).
The colours follow a blue-to-red gradient, where blue indicates a lower likelihood and red indicates a higher likelihood. The percentage displayed below for each hazard and threat represents the highest impact of the threat on food sector operations in the event of its occurrence. The threats and hazards are compared within each of the five categories and are arranged in descending order, with the highest impact at the top and the lowest impact at the bottom within each category.

Finally, Figure 7 also highlights socio-cultural and demographic hazards, emphasizing the equal importance of "demographic trends," "generational renewal," and "changes in consumer preferences and food choices," particularly for long-term planning. "Demographic trends," such as urbanization and an aging population, challenge food production and distribution, while "generational renewal" reflects difficulties in attracting younger workers to food-related fields, threatening labour sustainability. Shifts in consumer preferences toward plant-based and sustainable foods and socio-cultural and demographic changes such as urbanization and generational renewal profoundly impact food security by driving demand for resource-intensive foods. These findings reveal that evolving demographics and consumer expectations will shape future food sector resilience and demand adaptive strategies. The latest should align with shifting population needs and preferences alongside logistical and environmental concerns. To this end, policies promoting sustainable consumption and addressing these trends are crucial for ensuring equitable and resilient food systems (Godfray et al., 2010; UN DESA, 2022).

5.1.3 Resilience Management

The resilience management section assesses the perceived importance of various interventions and policies to mitigate risks and enhance resilience in food systems. Annex A includes the graphs for each intervention and policy, showing each scale's percentages (ratio) (1-5). Figure 8 presents the calculated Mean Score (± standard deviations on a 5-step scale of "not important" =1 to "very important" =5) of the 29 targeted interventions on a scale of 1 to 5 that could foster food systems' resilience against short- and long-term shocks and stresses. All interventions were rated as necessary to very important (scores >3), with climate change mitigation policies, investments in research and innovation, crisis response mechanisms, and policies addressing geopolitical instability receiving scores above 4, highlighting their importance. While the scores for interventions were generally close, the analysis revealed significant differences between them. For instance, climate change mitigation policies scored significantly higher than adaptability in trade regulations, exceptional EU financial support, unrestricted movement of commodities, and market interventions, reflecting their focus on urgent environmental drivers of food insecurity.

Similarly, crisis response mechanisms were rated significantly higher than adaptability in trade regulations, market interventions, and the promotion of shorter food supply chains, reflecting their perceived importance in effectively managing emergencies. Policies targeting geopolitical instability, conflict, and terrorism scored significantly higher than measures aligned with demographic trends and the promotion of shorter food supply chains, emphasizing their crucial role in global stability. Investments in research and innovation were prioritized over exceptional EU financial support, market interventions, and unrestricted movement of commodities, indicating a preference for long-term solutions through technological advancements. Lastly, policies aimed at generational renewal scored significantly higher than adaptability in trade regulations and market interventions, highlighting their importance in ensuring the sector's sustainable agricultural practices and continuity. These findings are in line with other studies. For instance, Béné et al. (2019) highlighted that investments in research and innovation are pivotal for developing sustainable agricultural practices, which are crucial for long-term food system resilience. Besides, integrating environmental and food policies through coherent frameworks is essential for addressing interconnected risks, bridging sectoral silos, and enhancing food system resilience (Nilsson et al., 2012; EC, 2021e).

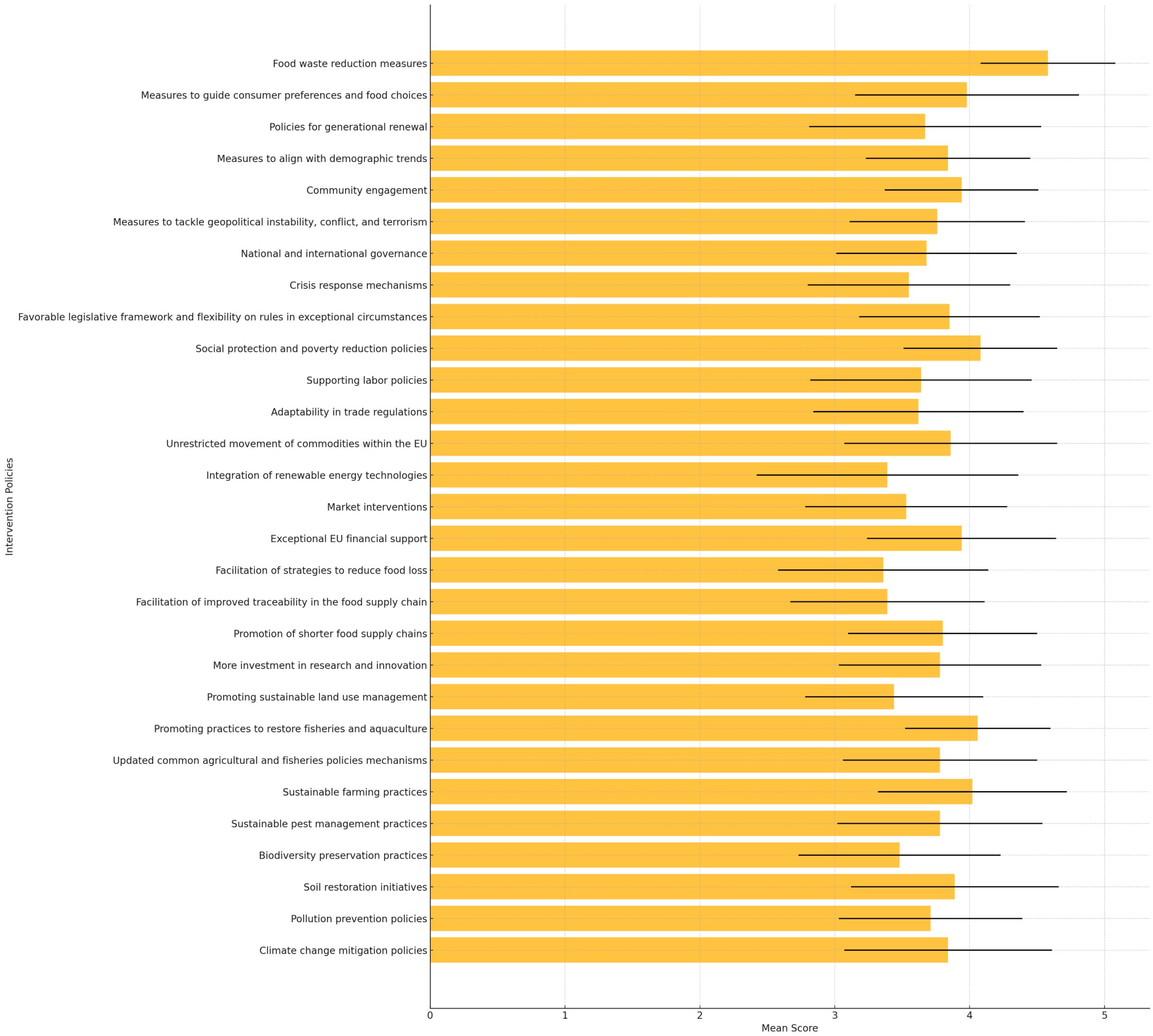

Figure 8 - Mean Scores of the 29 targeted interventions based on the answers of the respondents on a 5-step scale of "not important" =1 to "very important" =5 of the 29 targeted interventions (Table 1) that could foster food systems' resilience against short- and long-term shocks and stresses.
Error bars represent the standard deviation (n=47-50), providing a measure of variability or uncertainty in the scores for each policy.

Figure 8 illustrates the survey responses across key food security dimensions, including risk assessments, crisis preparedness, sustainability measures, resilience planning, governance participation, commodity reporting, digital communication use, online data platforms, and early warning systems. Organizational preparedness across the food sector reveals notable gaps and areas for improvement. While 43.4% of organizations conduct risk and vulnerability assessments to address potential disruptions, over half do not, highlighting significant readiness challenges (Figure 8a). Similarly, 39.6% have implemented crisis preparedness measures, such as early warning systems and incident reporting, but most lack these mechanisms, leaving them vulnerable to disruptions (Figure 8b). Nearly half of the organizations adopt long-term resilience initiatives, including renewable energy integration, precision farming, and diversified input sourcing (45.3%); however, many still fall short of comprehensive sustainability planning (Figure 8c). Few organizations (28.3%) have structured resilience plans, with most relying on ad hoc approaches that may undermine effective responses to sector-wide crises (Figure 8d). Governance collaboration shows mixed results, with 49.1% participating in platforms like national food security schemes or international organizations, though inconsistent involvement indicates potential for broader engagement (Figure 8e). Data sharing is also limited, with 32.1% of organizations exchanging commodity stock information with stakeholders, reducing transparency and coordinated crisis response capabilities (Figure 8f). Besides, only 26.4% of the organizations use dedicated digital communication mechanisms for timely reporting, with 64.2% lacking such tools (Figure 8g). Although nearly half (45.3%) use online observatories and data hubs to track critical food security factors such as weather and market conditions (Figure 8h), a significant proportion (64.2%) lacks early warning systems (Figure 8i), missing critical opportunities for preparedness. The importance of robust frameworks to enhance organizational preparedness, comprehensive monitoring, and early warning systems has been highlighted for mitigating food security risks (Weber and Cisneros, 2018). The OECD (2016) also emphasized the need for policy coherence, advocating for integrated approaches that align diverse policy areas to strengthen resilience and preparedness in addressing food security challenges.

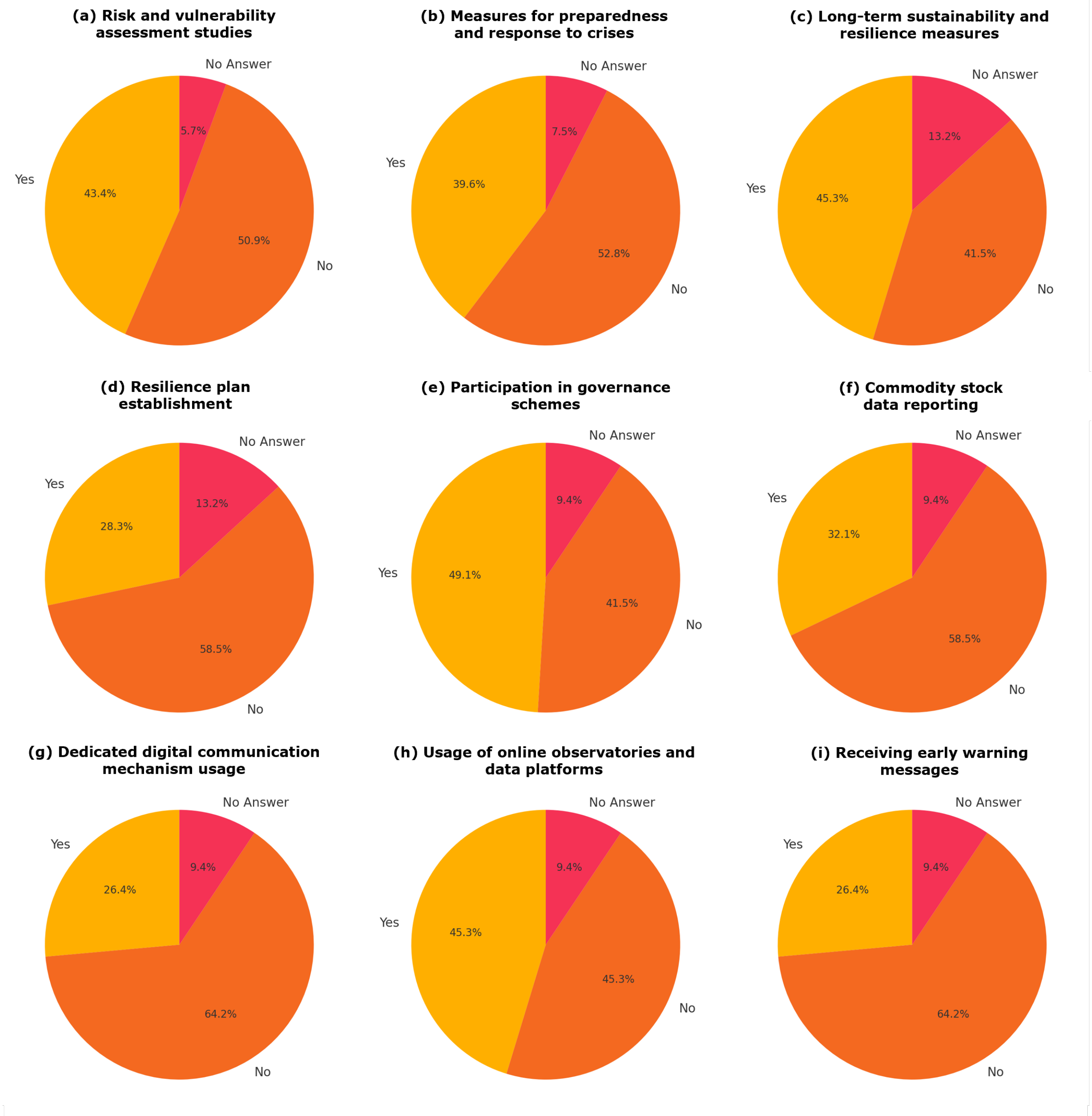

Figure 9 – Distribution of survey responses ("Yes," "No," and "No Answer") across various food security dimensions and organizational preparedness. (a) risk and vulnerability assessment studies; (b) measures for preparedness and response to crises; (c) long-term sustainability and resilience measures; (d) resilience plan establishment; (e) participation in governance schemes; (f) commodity stock data reporting; (g) dedicated digital communication mechanism usage; (h) usage of online observatories and data platforms; and (i) receiving early warning messages.

5.2 Ad Hoc Questionnaires' Results

An ad-hoc questionnaire was designed to complement the EU survey, incorporating multiple-choice, Likert scale, and open-ended questions to collect qualitative insights, enabling participants to elaborate the SecureFood's sector-specific case studies in greater depth. The questionnaire was organized into two sections: (i) food value chain and (ii) policy and resilience management framework (Annex B).

The first focused on gathering information on the selected food value chain (grains, dairy, fruits and vegetables, and fish and aquaculture) and the organization's role in the supply chain (e.g., production, processing, retail). It also collected data on the organization's country of operation, additional countries involved, and whether it exports commodities within or outside Europe. After that, the questionnaire asked respondents to assess listed hazards and threats using a 3-point Likert scale (Low=1, Medium=2, High=3) across three dimensions: likelihood of occurrence (short- or long-term), vulnerability of services, and potential impact if materialized. Respondents assessed various risks, including environmental (e.g., droughts, floods, soil degradation, biodiversity loss), operational (e.g., infrastructure failures, cyberattacks, supply disruptions), economic (e.g., market volatility, financial crises), and societal (e.g., population growth, labour shortages, migration). Additional considerations included governance issues, policy inadequacies, and social challenges like unrest or consumer behavior. Respondents were also asked to describe their interconnectedness and interdependencies within the supply chain and with supporting industries (e.g., logistics, packaging) and actors supporting the functioning of the chain (e.g., logistics services, packaging material). They were also invited to identify food security challenges and outline their top priorities for enhancing food system resilience based on the EU's definition of resilience.

In the second section, the questionnaire explored with open-ended questions respondents' perspectives on compliance with legislative frameworks, adherence to guidelines, and implementation of food supply and security standards. It assesses whether organizations conduct risk and vulnerability assessments to prepare for potential disruptions and apply technical, operational, or organizational measures for crisis preparedness and response. Long-term sustainability measures (e.g., renewable energy, waste reduction, precision farming) and contingency planning practices were also examined, alongside dedicated resilience plans. Respondents were asked about participation in governance schemes, stakeholder collaboration for crisis management, digital communication tools, and commodity stock reporting. Additionally, the survey investigated the use of online observatories for food-related data, early warning mechanisms for crisis identification, and desired functionalities in a digital twin to address food supply chain challenges. Likewise, the questionnaire explored an interest in SecureFood frameworks, models, and digital tools for fostering food security and resilience, such as risk assessment, resilience governance, digital twins, and early warning mechanisms. Respondents were asked to indicate which solutions they would incorporate into their case studies and identify existing systems they use for potential integration. Likewise, the questionnaire evaluated the desired characteristics of food security technologies in a multiple-choice approach, emphasizing reliability, interoperability, usability, modularity, scalability, and autonomy to improve preparedness and crisis response. Finally, follow-up consultations with the responders allowed for clarifications and additional input regarding the open-ended questions, ensuring that the findings reflect a well-rounded view of sectoral vulnerabilities and resilience capacities.

The ad hoc questionnaire has been distributed among beneficiaries and their members, stakeholders, and end users involved in the four SecureFood case studies: (i) grain, (ii) milk and dairy, (iii) fruits and vegetables, and (iv) fish and aquaculture. 38 completed questionnaires were collected and analysed to determine response percentages. The Mean Risk Exposure (± standard deviation) and the Mean Risk Index (± standard deviation) were calculated based on the responses to the questionnaire (which assessed Likelihood, Vulnerability, and Potential

Impact for each case study). These responses were rated on a scale of 1 to 3 and analysed using the following equations (adapted from Bertolozzi-Caredio et al., 2023):

- Risk Exposure (1-9) = Potential Impact (1-3) × Likelihood of Occurrence (1-3)
- Risk Index (1-27) = Risk Exposure (1-9) × Vulnerability (1-3)

For the grain sector, 15 responses were collected: one from Greece, two from Ukraine, and twelve from the Czech Republic. Czech respondents primarily represented processing, packaging, and transport/logistics, while the Greek respondents were a consumer association, and Ukrainian participants were mainly involved in production and processing. Most companies and organizations reported a primary focus on their domestic markets, though private sector respondents involved in exporting indicated an emphasis on EU markets.

In the milk and dairy sector, 14 responses were received: seven from Greece, one from Finland, and six from the Czech Republic. Czech respondents were engaged in processing, packaging, and logistics, while Greek participants included one consumer association, one research organization, and companies involved in production, processing, packaging, and logistics. Two Greek companies also participated in wholesale, while the Finnish company focused on production. While most businesses concentrate on national markets, private sector participants showed a global scope, exporting within the EU and internationally.

Six responses were collected for the fruits and vegetables sector: one from Greece, two from Portugal, and three from Slovenia. Respondents were involved in production, packaging, wholesale, and retail, with the Greek respondent representing a consumer association. Operations were national primarily, though two companies indicated exports outside Europe.

Lastly, three responses were received in the fish and aquaculture sector: one from a Greek consumer association, one from a Greek research center, and one from a private company in Belgium. The Belgian company provided insights covering the entire supply chain, from production to wholesale and consumption, reflecting a comprehensive industry perspective.

5.2.1 Critical Hazards and Threats for Each Sector

Figure 10 presents the main hazards identified for each sector and their potential impacts and implications for resilience. These hazards reflect unique vulnerabilities within each industry, highlighting where targeted interventions are essential to strengthen adaptive capacity and mitigate risks.

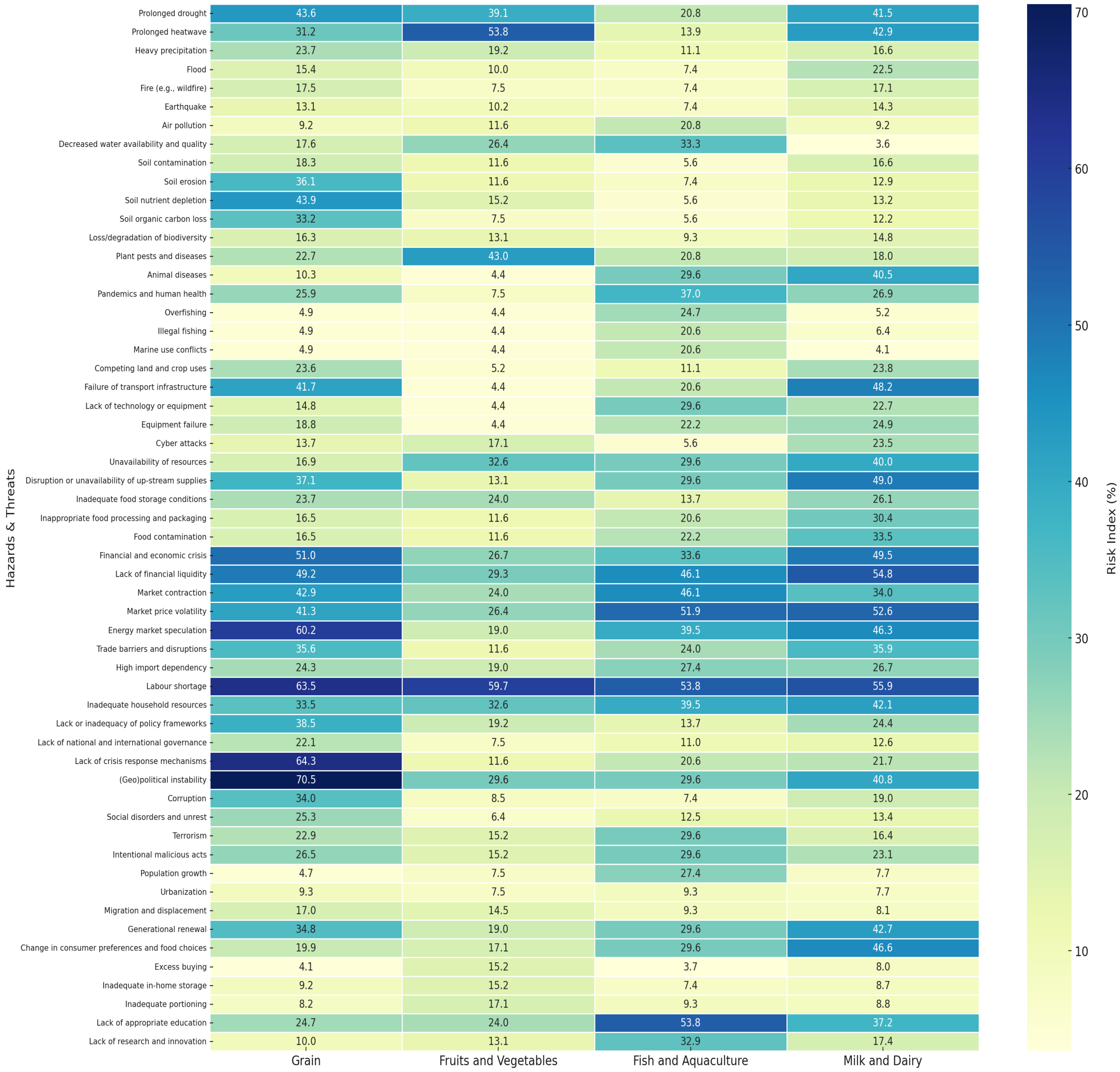

Figure 10 – Hazards and threats with the highest Risk Index (&) for the grain, fruits and vegetables, fish and aquaculture, and milk and dairy sectors.

Grain Sector

- **Energy market speculation:** The grain sector is susceptible to price fluctuations, as energy is essential for operating machinery, transportation, and processing facilities. Speculative changes in energy markets lead to price volatility, increasing operational costs unpredictably. This volatility limits producers' ability to plan budgets and secure resources, particularly for energy-intensive processes such as planting and harvesting. Respondents indicated that reliance on renewable energy sources and improved energy management practices could help buffer against market fluctuations.
- **Labor shortage:** Factors like aging, high costs, and health crises present a critical challenge, affecting labour-intensive tasks such as planting, tending, and harvesting crops. As the workforce ages and fewer young people enter agriculture, a significant gap in skilled labour impacts productivity and operational flexibility. Respondents highlighted the need for

workforce development initiatives, including training and incentives, to attract younger workers and maintain a stable labour force.

- **Lack of crisis response mechanisms:** The absence of effective mechanisms leaves the grain sector vulnerable during emergencies, such as natural disasters or supply chain disruptions. Without structured plans, companies face delays and inefficiencies when responding to unforeseen events, leading to financial losses and supply shortages. Participants stressed the importance of implementing structured crisis management protocols, including contingency planning and inter-organizational coordination, to strengthen resilience against potential crises.
- **(Geo)political instability, conflicts, and war:** They affect the grain sector by disrupting trade routes, limiting access to critical inputs, and creating resource competition. Political unrest can lead to export restrictions, increased tariffs, and blockades for grain producers dependent on stable international markets. Respondents suggested that policy measures supporting trade diversification and regional resilience could mitigate the impact of geopolitical risks on the sector's supply chain.

Milk and Dairy Sector

- **Lack of financial liquidity:** Financial liquidity is crucial in the dairy sector, where high operational costs (especially for feed and energy) are typical. Without sufficient liquidity, dairy farms struggle to cover expenses during economic downturns, leading to decreased production or temporary closures. Respondents highlighted the importance of financial safety nets, such as subsidies or access to low-interest loans, to support farms during economic strain and maintain consistent production.
- **Market price volatility:** Market price fluctuations for dairy products and feed materials pose a significant threat, affecting revenue stability and resource affordability. Price volatility makes it difficult for dairy producers to plan budgets and secure inputs at stable costs, leading to profit uncertainty. Respondents recommended policies to stabilize prices and suggested tools like demand forecasting and supply chain monitoring to improve resilience against unpredictable market conditions.
- **Labor shortage:** Labor availability is a pressing issue for the dairy sector, where skilled labour is necessary for animal care and milk processing tasks. Shortages, driven by aging workforces and rising labour costs, limit the sector's ability to operate efficiently and maintain product quality. Respondents proposed investment in workforce training programs to address these challenges and suggested automation in specific processes to reduce dependency on manual labour.

Fruits and Vegetables Sector

- **Prolonged heatwaves:** These are a critical environmental threat to the fruits and vegetables sector, directly impacting crop health, quality, and yield. High temperatures increase dehydration risks for plants, leading to lower-quality produce and higher irrigation demands. Prolonged heat can also disrupt the timing of harvests, making produce more susceptible to spoilage. Respondents recommended adaptive agricultural practices, such as shade structures, water-efficient irrigation systems, and drought-resistant crop varieties, to counteract heatwave impacts.
- **Labor shortage:** The fruits and vegetables sector depends heavily on seasonal labour, especially for harvesting tasks. Workforce shortages disrupt harvesting schedules and can lead to significant crop spoilage and financial losses. Respondents emphasized the importance of reliable labour access policies, such as seasonal labour programs and wage

support initiatives, to ensure an adequate labour supply. Automation in harvesting was also suggested as a longer-term solution to alleviate dependency on seasonal workers.
- **Plant pests and diseases:** They are significant threats to the fruits and vegetables sector, as they can quickly devastate crops, reduce yields, and necessitate costly interventions. Climate variability and global trade increase the exposure to invasive pests and pathogens. Respondents stressed the need for pest management practices, including biological control agents and crop rotation, and investment in early detection tools and disease-resistant plant varieties.

Fish and Aquaculture Sector

- **Market price volatility:** The fish and aquaculture sector is highly vulnerable to fluctuations in market prices for fish products and feed inputs. Price volatility affects revenue stability and complicates financial planning, particularly for smaller producers. Respondents noted that market forecasting and financial support mechanisms could help manage price fluctuations, ensuring consistent profitability and reducing the financial strain on producers.
- **Labor shortage:** Skilled labour shortages impact productivity in aquaculture, particularly in tasks requiring expertise, such as fish health monitoring and processing. As with other sectors, aging workforces and high labour costs limit operational flexibility and resilience. Respondents suggested workforce development initiatives, including training programs specific to aquaculture, to attract younger workers and ensure adequate staffing levels.
- **Lack of appropriate education and awareness:** There is a knowledge gap regarding sustainable practices and resilience strategies in the fish and aquaculture sector. Limited awareness among operators about biosecurity measures, environmental impacts, and sustainable resource management makes the industry more vulnerable to disruptions. Respondents highlighted the importance of education programs that focus on sustainability, biosecurity, and best practices, which could improve overall sector resilience.

5.2.2 Common Resilience Challenges Across the Case Studies

The ad hoc questionnaires identified several shared challenges across the four sectors, emphasizing areas where SecureFood's interventions can offer broad benefits to improve resilience. The findings highlight critical factors impacting food security, regulatory compliance, and digital tool adoption across sectors.

- **Supply chain stability and interdependency management:** All sectors rely on complex, interconnected supply chains where disruptions at any stage can cause cascading effects. For example, a delay in grain transport can impact dairy operations that depend on feed. This interdependent structure calls for enhanced supply chain management tools to identify potential bottlenecks and ensure quick responses to minimize disruptions. Respondents across sectors expressed interest in tools and frameworks to map these interdependencies better and understand the systemic impacts of disruptions.
- **Workforce vulnerabilities and labour access:** Workforce challenges emerged as common challenges, particularly labour shortages and high workforce costs. Each sector is experiencing shortages in skilled labour, whether seasonal or long-term, which affects productivity and operational continuity. Participants emphasized the need for labour policies that support sustainable workforce availability, including programs for seasonal labour in agriculture and training initiatives. Automation in specific processes was also suggested, particularly in labour-intensive sectors like fruits and vegetables.

- **Resource constraints and economic resilience:** Economic pressures such as market volatility, resource price fluctuations, and limited access to financing were significant concerns. Each sector needed financial mechanisms, such as accessible credit and subsidies, to manage these fluctuations and maintain operational stability. Trade policies that promote market stability and protect local producers were also suggested, as respondents noted that access to affordable resources is crucial for their sector's resilience.
- **Compliance with standards but gaps in crisis preparedness:** Most sectors reported adherence to international food safety and quality standards (e.g., FAO, WHO, Global GAP). However, there is a gap in food security and crisis preparedness protocols, as existing standards often lack guidelines addressing resilience. Respondents called for dedicated regulatory support to enhance sector-specific crisis management capabilities, including structured guidance for resilience planning.
- **Interest in digital tools with knowledge gaps:** There was substantial interest in digital tools like supply chain monitoring, early warning systems, and scenario modelling to enhance resilience. However, many respondents noted gaps in understanding how to apply these tools effectively. They expressed a need for practical examples, case studies, and training to help maximize the potential of these technologies. Desired features include reliability, interoperability, and usability, with tools that facilitate real-time decision-making to improve crisis response times.
- **Frameworks and models' interest:** Across sectors, respondents were interested in resilience frameworks for risk and vulnerability assessments, interdependency mapping, and early warning systems. While participants showed curiosity about advanced models like digital twins and 3D XR-based simulators, many struggled to see practical applications due to limited familiarity. Respondents suggested that SecureFood provide demonstrations and use cases to illustrate how these frameworks and tools could enhance resilience in their specific operations.

5.2.3 Unique Sector Resilience Priorities

In addition to commonalities, each sector reported unique priorities that reflect its specific risks and operational needs. These distinct outcomes offer targeted insights for SecureFood to tailor its interventions effectively:

Grain Sector

- **Focus on climate-resilient crop strategies:** Grain sector respondents prioritized climate resilience by developing drought-tolerant crop varieties and advanced irrigation systems. Given their dependency on stable environmental conditions, grain producers highlighted the need for technologies that address climate-induced risks, such as soil degradation and unpredictable weather. Respondents emphasized that climate adaptation would help maintain stable yields, reduce crop losses, and sustain profitability in an increasingly variable climate.
- **Trade policy and market stability:** Grain producers flagged trade barriers and market volatility as significant risks that limit their ability to compete globally. The sector called for policy interventions that promote fair competition, stabilize prices, and provide financial assistance to small farmers. Respondents indicated that better trade policies could protect local production and reduce dependence on international markets, thus bolstering resilience against economic shocks and geopolitical tensions.
- **High interest in interdependency mapping:** There was a strong interest in interdependency mapping to understand better the relationships and risks between

production stages and supply chain links. Grain stakeholders see this as essential for proactive resilience planning, as it enables them to anticipate and address how disruptions in one part of the chain affect others. Interdependency mapping would support more strategic decision-making and efficient resource allocation.

Milk and Dairy Sector

- **Animal health and veterinary support:** The dairy sector underscored the importance of veterinary services and disease prevention as essential resilience factors. Heat stress from climate variability directly affects animal welfare and milk production, making livestock health management crucial for stability. Respondents recommended veterinary health monitoring systems and climate-adapted shelters to mitigate disease risks and sustain productivity under extreme temperatures.
- **Financial stability as a resilience measure:** Dairy respondents identified financial liquidity and access to credit as critical for managing resource costs, especially for feed and energy. Financial support mechanisms, like credit lines or subsidies, were suggested to provide a financial buffer against market instability. With access to liquidity, dairy producers could better navigate economic downturns and continue essential operations without compromising animal health or product quality.

Fruits and Vegetables Sector

- **Flexibility to adapt to market fluctuations:** Respondents emphasized the need for flexibility to quickly adapt to market changes and seasonal demands. A dynamic supply chain and multi-sourcing strategy were essential for resilience, with flexible logistics and diversified sourcing helping ensure product availability despite disruptions.
- **Sustainable practices and resource conservation:** Sustainability emerged as a key focus, with respondents prioritizing eco-friendly practices like water conservation, soil health, and waste reduction. Sustainable farming was seen as a strategy for resilience and market appeal, with consumers favouring green products. Participants showed interest in tools like water-saving tech and carbon footprint tracking to support these efforts.
- **Demand for real-time monitoring:** Respondents valued real-time supply chain tracking tools for their ability to model seasonal production impacts and predict demand shifts, aiding in precise production and distribution planning.

Fish & Aquaculture Sector

- **Intensive focus on water quality monitoring:** Water quality is vital for production, as temperature, salinity, or pollution levels directly impact fish health and yield. Respondents stressed the need for tools that monitor marine and freshwater conditions, allowing producers to respond proactively to adverse changes. Real-time water quality monitoring could mitigate risks, support sustainable practices, and ensure that environmental conditions remain conducive to aquaculture.
- **Marine-specific threats and ecosystem management:** Unique to this sector are challenges such as invasive species, illegal fishing, and marine resource conflicts. Respondents highlighted the need for collaborative management involving public and private stakeholders to maintain marine ecosystem health. This collaboration would

support enforcing sustainable fishing practices, managing resource allocation, and protecting fish stocks from over-exploitation.

- Disease prediction: Disease outbreaks constitute a significant threat, as they can lead to large-scale losses in fish populations. Respondents expressed interest in digital tools that could predict disease risks through early warning indicators and real-time fish health monitoring. Digital twins were valuable for modelling disease spread and implementing biosecurity measures, reducing the economic impacts of disease outbreaks, and enhancing overall sector resilience.

5.2.4 Input to SecureFood's Taks and Work Packages

The insights and data gathered in this deliverable, D2.1, play a crucial role in shaping SecureFood's upcoming tasks and work packages by clearly understanding food security vulnerabilities and resilience drivers within the EU. For Task 2.3, these validated drivers and resilience needs will be translated into specific user requirements, ensuring that the solutions developed by SecureFood directly address sector-specific needs across various EU food systems. This alignment supports user-centred tool development that meets real-world operational and resilience challenges. Furthermore, Task 2.4 will use the detailed analysis in D2.1 to inform the design of a high-level reference architecture. This architecture will interconnect key food security drivers with intervention strategies, creating a structured foundation that guides SecureFood's implementation of models, digital tools, and governance frameworks. In WP3, especially within Task 3.1, the identified drivers and vulnerabilities support scenario-building activities that simulate potential disruptions and resilience strategies. These scenarios will allow WP3 to conduct foresight analyses, assessing the impact of various resilience interventions on the food system and identifying the most effective pathways for enhancing food security. The findings in D2.1 also significantly impact WP6, which is dedicated to co-creation, testing, and scaling up innovations within SecureFood. By defining practical scenarios, structuring case studies, and establishing evaluation metrics, WP6 will apply D2.1's findings to validate the project's efficiency and effectiveness. This includes training end-users on resilience-building strategies and measuring the performance of SecureFood innovations in real-world settings. D2.1 contributes foundational knowledge through these inputs and actively shapes SecureFood's strategic responses, ensuring the project's outcomes are impactful, applicable, and aligned with EU food security needs.

6 Conclusions

The completion of D2.1 marks a key milestone for SecureFood in building a resilient and secure EU food system. This deliverable is crucial for advancing the project's objectives in scenario development, foresight, and targeted interventions, all aligned with EU priorities on sustainability, resilience, and adaptability. SecureFood aims to establish a robust framework addressing the complexity and interdependence of food systems. Using a structured methodology and comprehensive background analysis, D2.1 explores dynamics affecting EU food security and provides resilience recommendations across sectors. The findings reveal essential resilience drivers, vulnerabilities, and intervention areas, setting a foundation for future phases, especially WP3 and WP6. Contributions from Tasks 2.1 and 2.2 emphasize the interconnectedness of food security pillars and the importance of a systems-thinking approach that balances short- and long-term needs. A key achievement of this deliverable is the comprehensive analysis of food security drivers across biophysical, technological, economic, political, and socio-cultural domains, each crucial for EU food system resilience. Biophysical factors like climate change and resource constraints underscore the need for adaptive practices, such as water-saving technologies and crop diversification, to withstand environmental stresses. Technological drivers—such as IoT, blockchain, and AI—hold transformative potential for food production and supply chain transparency but require robust data management and accessibility solutions. SecureFood's emphasis on digital tools addresses these challenges through data-driven decision-making and real-time monitoring. Economic factors, including price volatility and trade dependencies, raise food insecurity risks, highlighting the need to strengthen local production and stabilize supply chains. Political and institutional drivers call for cohesive policies across the EU, supporting sustainability and trade stability. Socio-cultural drivers, influenced by urbanization and changing consumer preferences, call for adaptable policies that cater to diverse regional needs. D2.1 provides a strategic framework to align these drivers with targeted interventions, emphasizing climate-resilient agriculture, digital transparency, and economic policies that promote stability. It advocates collaborative governance and stakeholder engagement to align strategies with priorities across the food system, ensuring SecureFood's interventions address varied needs effectively.

Insights from SecureFood's case studies and stakeholder feedback validate findings from the literature review, offering essential perspectives on food security risks and resilience strategies. Through the EU Survey and Ad Hoc Questionnaires, stakeholders revealed regional and sectoral differences in resilience needs across the EU, underscoring the need for context-specific approaches. Coastal regions, for example, emphasized fisheries and aquaculture sustainability, while landlocked areas prioritized crop resilience and water scarcity. Sectoral case studies on grains, dairy, fruits and vegetables, and aquaculture highlighted unique resilience needs, with soil health critical for grains, climate resilience for aquaculture, and market stability for dairy. Quantitative data from the Ad Hoc Questionnaire helped calculate Risk Exposure and Risk Index values for each sector, enabling SecureFood to identify priority areas for intervention. Qualitative feedback further illuminated sector-specific challenges, showing how different categories are affected by resilience drivers. These findings are instrumental in guiding WP3's scenario development and WP6's testing phase, establishing a solid foundation for modelling potential disruptions and resilience strategies. By aligning these strategies with sector needs, SecureFood can implement targeted interventions to address each category's vulnerabilities, enhancing adaptability within the EU's food systems. Analysing drivers, stakeholder feedback, and case studies will inform WP3's development of scenarios that simulate potential disruptions and test resilience strategies. This deliverable's in-depth understanding of sectoral vulnerabilities will enable WP3 to create realistic and applicable resilience scenarios.

Furthermore, WP6's co-creation and testing phase will apply these insights in real-world case studies, validating SecureFood's resilience models, frameworks, and tools. Working with end-users, WP6 will evaluate the feasibility, scalability, and impact of proposed resilience solutions, advancing the project's goal of a robust and adaptive food system. Ultimately, these outcomes highlight the need for cohesive policies to support resilient food systems across different regions and sectors. In conclusion, D2.1 is a cornerstone for the SecureFood project, providing a strategic roadmap for addressing food security challenges and enhancing resilience across the EU. Its deliverable promotes a systems-thinking approach that balances short- and long-term needs, providing frameworks for multi-level resilience and context-specific interventions. As the project progresses, insights from D2.1 will be vital in shaping a food system prepared for challenges like climate change and market shifts, supporting sustainable food security across the EU.

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Annex A

EU Survey Questionnaire list of questions:

General Information		
1	Which type of stakeholder do you represent?	☐ Private entity ☐ Coperatives, Associations and NGOs ☐ National or EU competent authority ☐ International organization ☐ Research institution ☐ Other (please specify)
2	In which food sector does the organization you represent operate?	☐ Grains ☐ Fruits and vegetables ☐ Milk and dairy ☐ Eggs and animal fats ☐ Roots and tubers ☐ Oilseeds, pulses, and treenuts ☐ Meat ☐ Fish, seafood and aquatic products ☐ Sugar, coffee, spices, and stimulants ☐ Beverage and alcohol ☐ Other (please specify)
3	In which stage(s) of the food supply chain does the organization you represent operate?	☐ Production ☐ Processing ☐ Packaging ☐ Transport and logistics ☐ Wholesale ☐ Retail ☐ Consumption ☐ Other (please specify)
4	In which country is the organization you represent based? (in case of an international organization, specify the country of the headquarters)	List with countries
5	Indicate the statement that reflects the status of the organization you represent.	☐ It operates only in one country (either EU or non-EU) ☐ It operates in >1 EU countries ☐ It operates in both EU and non-EU countries
5	What is the size of the organization you represent?	☐ Micro-sized (<10 workers) ☐ Small-sized (10-49 wokers) ☐ Medium-sized (50-250 workers) ☐ Large-sized (>250 workers)
6	Does the organization you represent export commodities within or outside Europe?	☐ Yes ☐ No ☐ Not applicable

Hazards and Threats		
7	Based on your perception, please prioritize the fundamental pillars of food security according to their significance in ensuring food security.	☐ Availability (steady and sufficient quantities of food for all) ☐ Access (physical and economic ability to obtain food) ☐ Utilization (proper consumption and nutritional value of food) ☐ Stability (consistent access to food over time) ☐ Agency (empowerment of individuals to make food-related decisions) ☐ Sustainability (ensuring food systems for future generations)
8	List the hazards and threats that have impacted in the past (historical incidents) the normal operation of the food sector you represent.	**Biophysical and Environmental** ☐ Changing climate and weather patterns, natural disasters (e.g., temperature changes, fires, extreme weather events, etc.) ☐ Environmental pollution ☐ Soil health deterioration (e.g., contamination, erosion, etc.) ☐ Natural resources and biodiversity degradation/loss ☐ Pests, invasive species, diseases, and pandemics ☐ Threats related to fisheries and aquaculture (e.g., overfishing, illegal fishing, etc.) ☐ Competing land and crop uses (e.g., conversion of cropland for biofuel feedstock cultivation) **Supply Chain** ☐ Inadequate supply chain performance (e.g., due to disruptions in transport and logistics, cyber attacks, technical risks, etc.) ☑ Increased food loss (e.g., inadequate storage conditions and packaging, food contamination, etc.) **Market and Economic** ☐ Financial (e.g., price volatility and fluctuations) ☐ Market (e.g., market instability) ☐ Energy supply disruptions and fluctuations in energy prices ☐ Trade (e.g., high dependency on imports, export-oriented production) ☐ Labour shortage ☐ Inadequate household resources **Political and Institutional** ☐ Geopolitical instability, conflicts and terrorism (e.g, war, unrest, malicious acts, etc.) ☐ Lack of legislative frameworks and governance **Socio-cultural & Demographic** ☐ Demographic trends (e.g., urbanization, ageing population, migration, etc.) ☐ Generational renewal (e.g., a lack of attractiveness in the food sector for younger generations) ☑ Change in consumer preferences and food choices ☑ Food Waste through consumption (e.g., excess buying, inadequate In-home storage)

9	List the hazards and threats that are most likely to affect your food sector and disrupt food security in the next 3 years (up to 5 answers).	**Biophysical and Environmental** ☐ Changing climate and weather patterns, natural disasters (e.g., temperature changes, fires, extreme weather events, etc.) ☐ Environmental pollution ☐ Soil health deterioration (e.g., contamination, erosion, etc.) ☐ Natural resources and biodiversity degradation/loss ☐ Pests, invasive species, diseases, and pandemics ☐ Threats related to fisheries and aquaculture (e.g., overfishing, illegal fishing, etc.) ☐ Competing land and crop uses (e.g., conversion of cropland for biofuel feedstock cultivation) **Supply Chain** ☐ Inadequate supply chain performance (e.g., due to disruptions in transport and logistics, cyber attacks, technical risks, etc.) ☐ Increased food loss (e.g., inadequate storage conditions and packaging, food contamination, etc.) **Market and Economic** ☐ Financial (e.g., price volatility and fluctuations) ☐ Market (e.g., market instability) ☐ Energy supply disruptions and fluctuations in energy prices ☐ Trade (e.g., high dependency on imports, export-oriented production) ☐ Labour shortage ☐ Inadequate household resources **Political and Institutional** ☐ Geopolitical instability, conflicts and terrorism (e.g, war, unrest, malicious acts, etc.) ☐ Lack of legislative frameworks and governance **Socio-cultural & Demographic** ☐ Demographic trends (e.g., urbanization, ageing population, migration, etc.) ☐ Generational renewal (e.g., a lack of attractiveness in the food sector for younger generations) ☐ Change in consumer preferences and food choices ☐ Food Waste through consumption (e.g., excess buying, inadequate In-home storage)

10	List the hazards and threats that are most likely to affect your food sector and disrupt food security by 2050 (up to 5 answers).	**Biophysical and Environmental** ☐ Changing climate and weather patterns, natural disasters (e.g., temperature changes, fires, extreme weather events, etc.) ☐ Environmental pollution ☐ Soil health deterioration (e.g., contamination, erosion, etc.) ☐ Natural resources and biodiversity degradation/loss ☐ Pests, invasive species, diseases, and pandemics ☐ Threats related to fisheries and aquaculture (e.g., overfishing, illegal fishing, etc.) ☐ Competing land and crop uses (e.g., conversion of cropland for biofuel feedstock cultivation) **Supply Chain** ☐ Inadequate supply chain performance (e.g., due to disruptions in transport and logistics, cyber attacks, technical risks, etc.) ☐ Increased food loss (e.g., inadequate storage conditions and packaging, food contamination, etc.) **Market and Economic** ☐ Financial (e.g., price volatility and fluctuations) ☐ Market (e.g., market instability) ☐ Energy supply disruptions and fluctuations in energy prices ☐ Trade (e.g., high dependency on imports, export-oriented production) ☐ Labour shortage ☐ Inadequate household resources **Political and Institutional** ☐ Geopolitical instability, conflicts and terrorism (e.g, war, unrest, malicious acts, etc.) ☐ Lack of legislative frameworks and governance **Socio-cultural & Demographic** ☐ Demographic trends (e.g., urbanization, ageing population, migration, etc.) ☐ Generational renewal (e.g., a lack of attractiveness in the food sector for younger generations) ☐ Change in consumer preferences and food choices ☐ Food Waste through consumption (e.g., excess buying, inadequate In-home storage)

11	List the hazards and threats that may have the highest impact in the normal operation of your food sector and its capacity to deliver sufficient, affordable, safe and nutritious food to people (up to 5 answers).	**Biophysical and Environmental** ☐ Changing climate and weather patterns, natural disasters (e.g., temperature changes, fires, extreme weather events, etc.) ☐ Environmental pollution ☐ Soil health deterioration (e.g., contamination, erosion, etc.) ☐ Natural resources and biodiversity degradation/loss ☐ Pests, invasive species, diseases, and pandemics ☐ Threats related to fisheries and aquaculture (e.g., overfishing, illegal fishing, etc.) ☐ Competing land and crop uses (e.g., conversion of cropland for biofuel feedstock cultivation) **Supply Chain** ☐ Inadequate supply chain performance (e.g., due to disruptions in transport and logistics, cyber attacks, technical risks, etc.) ☐ Increased food loss (e.g., inadequate storage conditions and packaging, food contamination, etc.) **Market and Economic** ☐ Financial (e.g., price volatility and fluctuations) ☐ Market (e.g., market instability) ☐ Energy supply disruptions and fluctuations in energy prices ☐ Trade (e.g., high dependency on imports, export-oriented production) ☐ Labour shortage ☐ Inadequate household resources **Political and Institutional** ☐ Geopolitical instability, conflicts and terrorism (e.g, war, unrest, malicious acts, etc.) ☐ Lack of legislative frameworks and governance **Socio-cultural & Demographic** ☐ Demographic trends (e.g., urbanization, ageing population, migration, etc.) ☐ Generational renewal (e.g., a lack of attractiveness in the food sector for younger generations) ☐ Change in consumer preferences and food choices ☐ Food Waste through consumption (e.g., excess buying, inadequate In-home storage)

Resilience Management			
12	Please assign a score to the following interventions, based on how important you deem they are for food security and food systems resilience (1 - not important to 5 - very important).		Climate change mitigation policies (e.g., climate-resilient crop varieties, early warning systems, etc.)
			Pollution prevention policies (e.g., managing emissions, carbon reduction, sustainable waste management, etc.)
			Soil restoration initiatives (e.g., reforestation, conservation tillage, cover cropping, etc.)
			Biodiversity preservation practices (e.g., habitat restoration, pollinator-friendly landscaping practices, etc.)
			Sustainable pest management practices (e.g., biological control, integrated approaches, crop rotation, etc.)
			Sustainable farming practices (e.g., organic farming, soil carbon sequestration, etc.)
			Updated common agricultural and fisheries policies mechanisms (e.g., measures to reduce mediators from farm to fork, sustainable fishers' management plants, etc.)
			Promoting practices to restore fisheries and aquaculture (e.g., marine protected areas, integrated multitrophic aquaculture, etc.)
			Promoting sustainable land use management (e.g., land use planning and zoning, considering both food and biofuels production, etc.)
			More investment in research & innovation (e.g., institutional research, IT solutions, Industry 4.0 applications, automation, etc.)
			Promotion of shorter food supply chains (e.g., facilitation of platforms for direct sales, logistical support for small-scale producers to access local markets, etc.)
			Facilitation of improved traceability in the food supply chain (e.g., for advanced quality control, tracking of food contamination, etc.)
			Facilitation of strategies to reduce food loss (support cold chain infrastructure, provide better storage facilities, educate on proper handling, etc.)
			Exceptional EU financial support (e.g., emergency relief funds, low-interest loans to agricultural businesses, subsidies for insurance premiums, etc.)
			Market interventions (e.g., price stabilization mechanisms, facilitate access to credit and financial instruments for small-scale producers, etc.)
			Integration of renewable energy technologies (e.g., adoption through subsidies and tax credits, supportive regulatory frameworks to accelerate their integration, etc.)
			Unrestricted movement of commodities within the EU (e.g., streamline customs procedures, harmonize regulatory standards, enhanced transportation networks, etc.)
			Adaptability in trade regulations (e.g., trade agreements with flexibility clauses, establish mechanisms for temporary tariff adjustments, offer trade incentives, etc.)
			Supporting labor policies (e.g., incentives for labor mobility to regions experiencing labor shortages, laws to ensure fair wages, training programs to enhance labor skills, etc.)
			Social protection and poverty reduction policies (e.g., provide financial assistance or subsidies to low-income households, promote income equality through policies, etc.)
			Favorable legislative framework and flexibility on rules in exceptional circumstances (e.g., subsidies, tax discounts, emergency waivers, etc.)
			Crisis response mechanisms (e.g., regularly updated plans at national and regional levels, rapid response teams, coordination among relevant agencies and stakeholders, etc.)
			National and international governance (e.g., transparent and accountable governance structures, foster collaboration between governments and international organizations, etc.)
			Measures to tackle geopolitical instability, conflict, and terrorism (e.g., enhance diplomatic efforts, strengthen security measures, humanitarian aid to affected populations, etc.)
			Community engagement (e.g., initiatives to promote local food production and distribution, workshops on sustainable farming practices, promotion of urban farming, etc.)
			Measures to align with the demographic trends (e.g., policies for urbanization challenges, support aging populations in rural areas, manage migration flows, etc.)
			Policies for generational renewal (e.g., mentorship programs to transfer agricultural knowledge from older to younger ones, grants for young farmers to access land and resources for agricultural production, etc.)
			Measures to guide consumer preferences and food choices (e.g., education for sustainable food choices, food labeling initiatives, campaigns for local and seasonal food markets, etc.)
			Food waste reduction measures (e.g., public awareness campaigns, collaboration with retailers to implement portion control measures and reduce oversized packaging, etc.)

13	Does the organization you represent conduct risk and vulnerability assessment studies as a proactive approach that allows the organization to anticipate and prepare for potential incidents that may compromise its normal operation, the food supply and food security?	☐ YES ☐ NO
14	Recent incidents, such as Russia's invasion to Ukraine and the COVID-19 pandemic, have outlined the importance of better preparedness and response to potential threats to food supply and food security in times of crises. Does the organization you represent apply any measures (either technical, operational or organizational) that support the preparedness and response to crises that may threaten the normal operation of your organization, food supply and food security (e.g., information sharing, incident reporting, stock data reporting, early warning mechanisms, etc.)?	☐ YES ☐ NO
15	While short term emergency/crisis response measures are important for safeguarding food security, they do not replace the importance of refocusing the food sector in the long run towards sustainability and resilience. This is an integral part of contingency planning. This reorientation of the food sector could foster food security in the medium and long-term. Do you apply any measures (either technical, operational or organizational) towards that direction (e.g., diversification of input sources, use of renewable energy, food loss and waste reduction, precision farming, less reliance on mineral fertilizers, etc.)? Please specify.	☐ YES ☐ NO
16	Have the organization you represent established and implemented a resilience plan (or national plan in case of competent authorities), specifying the measures of Questions 14 and 15?	☐ YES ☐ NO

17	A well-structured governance scheme for food security and food systems resilience promotes the collaboration of public and private stakeholders on commonly defined and accepted strategic goals, roles and responsibilities. Does the organization you represent participate in such structured governance processes, at national or international level, sharing its perspectives and expectations from food security and being actively engaged in the resilience building efforts of the food sector?	☐ ☐	YES NO
18	Does the organization you represent report data on commodities stocks to other stakeholders (e.g., food actors, competent authorities at national or EU level, etc.), allowing them to have an acurate picture of commodities availability?	☐ ☐	YES NO
19	If yes, please specify how this reporting is performed.	☐ ☐ ☐	Oral (e.g., phone calls) Written (e.g., emails, formalized written reports) Digital (e.g., through a dedicated digital mechanim)
20	Does the organization you represent use a dedicated digital communication mechanism allowing information sharing before and during crises and the timely reporting of food security-related incidents to competent authorities and other stakeholders?	☐ ☐	YES NO
21	Does the organization you represent use any online observatories and data platforms/hubs for getting infrormed on food-related factors, such as weather data, market variables, socio-economic data, etc.?	☐ ☐	YES NO
22	Does the organization you represent receive early warning messages enabling the timely identification of the signs of an upcoming crisis?	☐ ☐	YES NO

Annex B

Ad – hoc Questionnaire list of questions:

Partner name ***(fill in)***	**Food Value Chain** ☐ Grains ☐ Fruits and vegetables ☐ Fish ☐ Aquaculture ☐ Milk and dairy	**Important note:** As you complete the questionnaire, please ensure that your responses consistently reflect **the specific food value chain** you have chosen.

General Information		
1	In which stage(s) of the food supply chain does your organization operate?	☐ Production ☐ Processing ☐ Packaging ☐ Transport and logistics ☐ Wholesale ☐ Retail ☐ Consumption ☐ Other (please specify):
2	In which country is your organization based? (in case of an international organization, specify the country of the headquarters)	Free text
3	If applicable, please list any other countries in which your organization operates.	Free text
4	Do you export commodities within or outside Europe? Please specify.	Free text

Hazards, Threats, Risks						
5	Food systems are characterized by increased complexity, which mainly arises from the interconnectedness and interdependencies among various elements, actors, processes, infrastructures and essential services. Please provide information on your most important interdependencies, considering those with the actors of the food supply chain itself (e.g., producers and retailers), but also with the actors that support the functioning of the chain (e.g., industries providing services on logistics and packaging material).	Free text				
			Likelihood	**Vulnerability**	**Impact**	**Comments/Clarifications (if any)**
6	For each listed hazard and threat, and using the 3-point Likert scale a) High, b)Medium, c) Low from the drop-down list, please indicate how **Likely** is that the threat/hazard will occur (either in the short or in the long-term), how **Vulnerable** your services are to the specific hazard/ threat and what is the extent of the potential **Impact** to your services if the hazard/threat materializes. ***Note:*** *If you have any comments or want to provide clarifications, please use* *Column H "Comments/Clarifications".*	Prolonged drought				
		Prolonged heatwave				
		Heavy precipitation				
		Flood				
		Fire (e.g., wildfire)				
		Earthquake				
		Air pollution				
		Decreased water availability and quality				
		Soil contamination				
		Soil erosion				
		Soil nutrient depletion				
		Soil organic carbon loss				
		Loss/degradation of biodiversity				
		Plant pests and diseases				
		Animal diseases				
		Pandemics and human health				
		Overfishing				
		Illegal fishing				
		Marine use conflicts				
		Competing land and crop uses (e.g., conversion of cropland for biofuel feedstock cultivation)				
		Failure of transport infrastructure and logistics				
		Lack of technology or equipment				
		Equipment failure				
		Cyber attacks				
		Unavailability of resources (e.g., fertilizers, energy, feed etc)				
		Disruption or unavailability of up-stream supplies				
		Inadequate food storage conditions leading to food loss				
		Inappropriate food processing and packaging leading to food loss				
		Food contamination				
		Financial and economic crisis				
		Lack of financial liquidity				
		Market contraction, concentration and unfair competition				
		Market price volatility				
		Energy market speculation				
		Trade barriers and disruptions				
		High import dependency				
		Labour shortage (e.g., due to aging, increased cost, pandemics etc)				
		Inadequate household resources				
		Lack or inadequacy of policy frameworks				
		Lack of national and international governance				
		Lack of crisis response mechanisms				
		(Geo)political instability, conflicts, war				
		Corruption				
		Social disorders and unrest				
		Terrorism				
		Intentional malicious acts				
		Population growth				
		Urbanization				
		Migration and displacement				
		Generational renewal (e.g., lack of attractiveness in the food sector for younger generations)				
		Change in consumer preferences and food choices				
		Excess buying				
		Inadequate in-home storage impacting food waste				
		Inadequate portioning and package sizes increasing food waste				
		Lack of appropriate education and awareness				
		Lack of research and innovation, and technological advances				

7	Which hazards, threats and challenges, related to food security, would you be interested in addressing through the SecureFood project? Please provide broad information on the use case scenarios you would be interested in covering. ***Note:*** *You can use the threats/hazards list provided in question 6, but you can also think of additional ones.*	Free text
8	What are your key priorities regarding food systems resilience? ***Note:*** *Resilience is defined as "the ability to prevent, protect against, respond to, resist, mitigate, absorb, accommodate and recover form an incident" (COM(2021)689).*	Free text

Policy and Resilience Management		
1	What is the national and/or international legislative framework that you need to comply with, regarding food supply and food security matters?	Free text
2	Do you adhere to any national and/or international guidelines/best practices regarding food supply and food security matters?	Free text
3	Do you implement any standards related to food security and food supply matters?	Free text
4	Is there a public authority at national level that is responsible for food security and food systems resilience matters? If yes, please specify.	Free text
5	Do you conduct risk and vulnerability assessment studies as a proactive approach that allows you to anticipate and prepare for potential incidents that may compromise the normal operation of your organization, the food supply and food security?	Free text
6	Recent incidents, such as Russia's invasion to Ukraine and the COVID-19 pandemic, have outlined the importance of better preparedness and response to potential threats to food supply and food security in times of crises. Do you apply any measures (either technical, operational or organizational) that support the preparedness and response to crises that may threaten the normal operation of your organization, food supply and food security? Please specify. Note: Technical measures refer to tools and technologies, such as early warning mechanisms, information sharing platforms, monitoring systems , etc. Operational measures refer to practical aspects of executing processes within an organization, such as emergency response protocols , etc. Organizational measures refer to the policies and structures within an organization that govern its operations, such as establishment of crisis management teams, the training programs , etc.	Free text
7	While short term emergency/crisis response measures are important for safeguarding food security, they do not replace the importance of refocusing the food sector in the long run towards sustainability and resilience. This is an integral part of contingency planning. This reorientation of the food sector could foster food security in the medium and long-term. Do you apply any measures (either technical, operational or organizational) towards that direction (e.g., diversification of input sources, use of renewable energy, food loss and waste reduction, rainwater harvesting, smart sensors for precision farming, less reliance on mineral fertilizers, farmer's training programs, policies with clear targets for reducing green house gas emissions , etc)? Please specify.	Free text
8	Do you have a dedicated resilience plan (or national plan in case of competent authorities), specifying the measures of Questions 6 and 7?	Free text
9	A well-structured governance scheme for short and long-term food systems resilience and food security promotes the collaboration of public and private stakeholders on commonly defined and accepted strategic goals, roles and responsibilities. Do you participate in such structured governance processes, at national or international level, sharing your perspectives and expectations from food security and being actively engaged in the resilience building efforts of the food sector? Please specify.	Free text

10	Contingency planning involves preparing for unexpected events or emergencies that could disrupt normal operations. As part of contingency planning, a collaborative approach between all public and private parties being part of the food supply chain is crucial to enhance preparedness, to quickly identify the signs of an upcoming crisis and to coordinate the response at all levels. Please provide information on the public and private stakeholders you collaborate with before, during and after crises, highlighting your role in crisis preparedness and response.	Free text
11	Do you use a dedicated digital communication mechanism allowing information sharing before and during crises, and the timely reporting of food security-related incidents to competent authorities and other stakeholders?	Free text
12	Do you report data on commodities stocks to other stakeholders (e.g., food actors, competent authorities at national or EU level , etc), allowing them to have an accurate picture of your commodities availability? If yes, please specify how this reporting is performed.	Free text
13	Do you use any online observatories and data platforms/hubs for getting infrormed on food-related factors, such as weather data, market variables, socio-economic data , etc? If yes, please list the observatories/hubs you are accessing. Moreover, please specify what kind of information you would be interested in getting by an online observatory/hub.	Free text
14	Do you receive early warning messages enabling the timely identification of the signs of an upcoming incident/crisis? If yes, please specify what kind of infomartion is received. If no, please indicate what kind of information you would be interested in receiving by an early warning mechanism.	Free text
15	A digital twin of a food supply chain could serve as a smart replica of the physical supply chain, mirroring the various functions and processes into a virtual space. The digital twin can use histrorical and real time data to simulate food supply chains' past, present and future. Moreover it can offer sychronization with the various processes and entities of food supply chains'. What specific functionalities would you like to see in the digital twin to address your challenges?	Free text