D1.2 First version of the Conceptual Framework and literature review

WP1: Stakeholder involvement in data-driven analysis of the food system in the search for new solutions

Subtask 1.1.2 Participatory theory building

Responsible Authors: Cristina Sagnotti; Fabio Bartolini (UNIFE)

Document information

Programme & Call	Horizon Europe: HORIZON-CL6-2023-GOVERNANCE-01
Project Acronym	SOSFood
Project Name	Sustainability Optimization for Secure Food Systems
Project Start Date	February 2024
Project Duration	48 months
Project Coordinators	Jesús Simal Gándara (UVigo) Eloy Miranda Garcia (UVigo)

Deliverable Title	First version of the Conceptual Framework and literature review
Deliverable Number	D1.2
Deliverable Type	Report
Dissemination Level	Public
Work Package	WP1 – Stakeholder involvement in data-driven analysis of the food system in the search for new solutions Subtask 1.1.2 Participatory theory building
Lead Beneficiary	UNIFE
Delivery date	M10 (November 2024)

Document History

Time	Status	Date	Author
01	First Version of the Conceptual Framework	31/03/2025	Fabio Bartolini (UNIFE) Cristina Sagnotti (UNIFE)
02	Final Version of the conceptual Framework	27/06/2025	Fabio Bartolini (UNIFE) Cristina Sagnotti (UNIFE)

Participants	Contact
Fabio Bartolini	fabio.bartolini@unife.it
Cristina Sagnotti	cristina.sagnotti@unife.it

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Executive Summary

This deliverable presents the initial version of the SOSFood project's conceptual framework. It is based on a literature review covering the food system's configuration, key actors, and boundaries, as well as the role of digitalisation and AI technologies in driving the transition towards a more sustainable food system.

The Conceptual Framework is developed using a two-step methodology. The current version includes the initial summary of the literature on the topic addressed. Thus, the following steps will be to co-create a validated version through a grounded test.

1. Introduction

The SOSFood project is designed to leverage data exploitation and Artificial Intelligence (AI) to provide a comprehensive overview of the European food system. The project aims to develop predictive tools to support stakeholders across the food value chain, fostering a more sustainable, resilient, and inclusive food system. This conceptual framework outlines the theoretical foundations underpinning the project, integrating multi-disciplinary insights and innovative technologies to address current and emerging challenges in the food sector. The first step in this process is establishing a Conceptual Framework that structures the food system's key aspects through the literature review and identifies its key components, relevant actors, boundaries, digitalisation outcomes and possible impacts.

2. Literature Review

2.1 Food System Configuration

The configuration of the food system is a complex and rapidly evolving topic, influenced by multiple interconnected factors. To fully understand this configuration, it is essential to examine the definition of food systems, their key components, the factors influencing their dynamics, and the existing models and frameworks.

2.1.1 Definition of Food Systems and Their Components

A food system encompasses all actors and their interconnected activities that add value at every stage, from production and aggregation to processing, distribution, consumption, and disposal of food products derived from agriculture, forestry, or fisheries (Raheem, Shishaev, & Dikovitsky, 2019; Sodano, 2024). It also includes the broader economic, social, and natural contexts in which these activities take place (Sodano, 2024). Furthermore, food systems are continuously shaped by advancements in science, technology, data management, and innovation. From this perspective, the key components of a food system include (Figure 1):

- ✓ **Food production**: activities related to crop cultivation, livestock rearing and fisheries.
- ✓ **Food processing and transformation**: processes that convert raw commodities into processed food products.
- ✓ **Distribution and retail**: activities involved in the transport, storage, and sale of food products to consumers.
- ✓ **Consumption**: food habits and preferences of consumers, as well as physical and economic access to food.
- ✓ **Disposal**: management of food waste and by-products resulting from food system activities.

Figure 1. Components of the food system

2.1.2 Key Factors Influencing Food System Dynamics

The dynamics of food systems are shaped by a range of interconnected factors (Figure 2), including:

Environment: Food systems both impact and are influenced by environmental changes. Soil quality, water availability, and climate conditions affect food production, storage, and distribution, ultimately influencing food security, dietary quality, and human health through exposure to contaminants (Fanzo et al., 2021). Climate change poses a major threat to food security and system stability, as extreme weather events, such as droughts, floods, and heatwaves, reduce crop yields and disrupt supply chains. At the same time, unsustainable food systems contribute to environmental degradation through greenhouse gas emissions, water and soil pollution, eutrophication, biodiversity loss, and deforestation (Anastasiou et al., 2022).

Policies and Regulations: Policies and regulations are fundamental in shaping food systems by influencing production methods, trade practices, pricing structures, and food safety standards. Effective regulatory frameworks ensure food security, environmental sustainability, and public health, but they also face challenges related to enforcement, market competition, and technological adaptation (Unnevehr, 2022).

Food safety regulations are a major component of food system policies, ensuring that agricultural products meet health standards.

Flexible and adaptive policies are essential to fostering innovation while maintaining food safety and environmental protection (Mahardhani, 2023). Regulatory frameworks must balance economic interests with sustainability goals, ensuring that food systems remain resilient in the face of climate change, resource limitations, and evolving consumer demands.

Consumer Preferences: Shifts in consumer demand are among the most influential factors reshaping the dynamics of food systems. In recent years, there has been a marked increase in interest towards health-conscious eating and more sustainable food choices. This trend is driven by greater awareness on the links between diet, health, and environmental impact (Gil et al., 2024). Consumers are increasingly opting for organic, plant-based, and locally sourced foods, as well as products that promise ethical sourcing and minimal environmental impact. This shift is being fuelled by a combination of factors such as growing concerns over climate change, biodiversity loss, and public health issues (e.g., the rise of lifestyle-related diseases such as obesity and diabetes).

Plant-based diets have gained popularity due to their perceived environmental benefits, such as reduced greenhouse gas emissions, water consumption, and land use compared to animal-based products. As a result, there is increasing demand for plant-based alternatives, such as meat substitutes, dairy-free products, and other environmentally friendly food options (Craig et al., 2023). Sustainability is no longer just a niche concern but a mainstream expectation, leading to the rise of eco-labels and certifications that inform consumers about the environmental and ethical standards behind food products.

In addition, ethical considerations are shaping consumer decisions, with concerns over animal welfare, labour conditions, and fair-trade practices pushing consumers toward more socially responsible purchasing choices (Peschel et al., 2025).

These shifts in consumer preferences are not only altering food production but also influencing food distribution and marketing strategies. Retailers and food producers are increasingly adapting to these demands by offering a wider range of products that align with these evolving consumer values. In response, brands are emphasizing their sustainability practices, ethical standards, and environmental commitments as key selling points to attract more environmentally and socially conscious consumers.

The transformation in consumer preferences is contributing to the diversification of the food system, with the emergence of new food trends, innovations, and market segments. As a result, food producers are being pressured to innovate and adapt to these preferences to remain competitive, creating both challenges and opportunities for businesses in the food industry.

Digitalisation: The integration of digital technologies, including the Internet of Things (IoT), artificial intelligence (AI), and blockchain, is transforming food production, processing, distribution, and consumption (Raheem, Shishaev, & Dikovitsky, 2019). While digitalisation enhances efficiency, traceability, and sustainability, it also raises concerns related to power dynamics, data privacy, and digital inequality.

Understanding the configuration of the food system requires a holistic approach that considers the interactions between its different components and the factors that influence its dynamics.

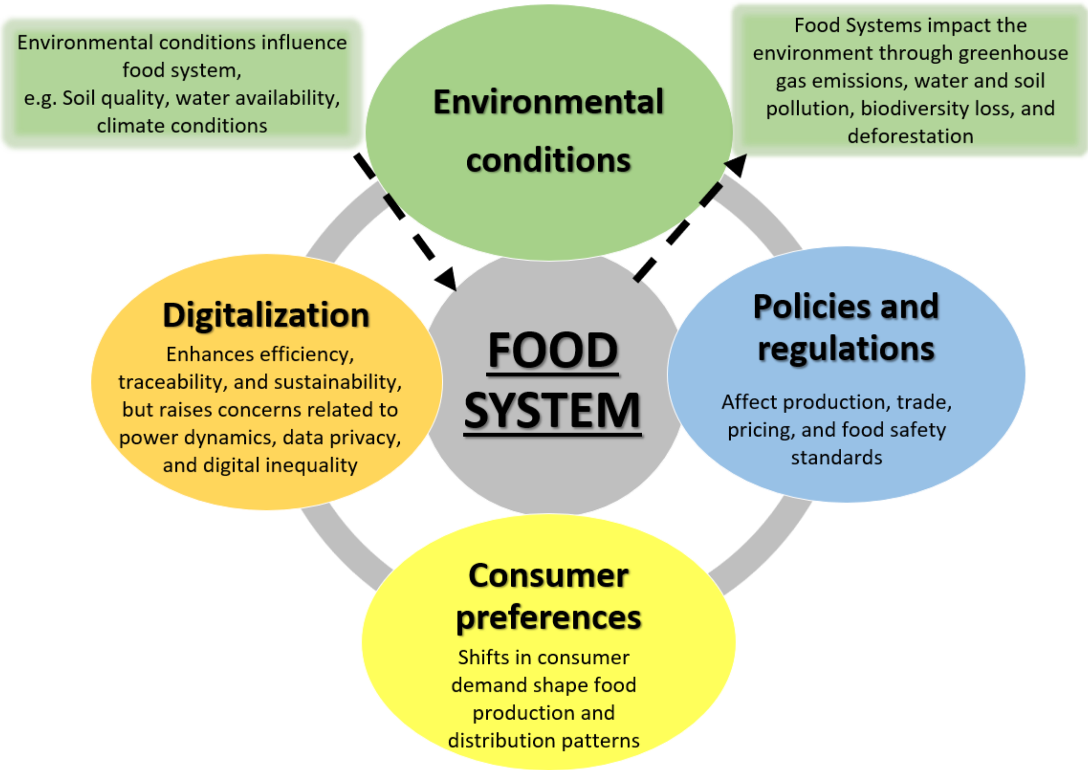

Figure 2. Key Factors Influencing Food System Dynamics

2.1.3 Challenges in the European Food System

The European food system faces a range of interconnected challenges spanning environmental, economic, social, and technological dimensions.

Environmental Sustainability: The European Union (EU) food system is a significant contributor to environmental degradation, accounting for approximately 30% of the EU's total greenhouse gas (GHG) emissions (Crippa et al., 2021). Agricultural activities occupy about 40% of the EU's land area, leading to substantial biodiversity loss and soil degradation (European Environment Agency, 2020). Transitioning to a circular food system could potentially reduce agricultural land use by 71% and per capita agricultural GHG emissions by 29%, while still meeting nutritional needs (van Zanten et al., 2023). Climate change, biodiversity loss, and soil degradation are pressing concerns. Agricultural production in Europe is increasingly affected by extreme weather events, rising energy costs, and stricter regulations on pesticide use. Food waste remains a critical issue, with approximately 59 million tonnes of food lost or wasted in the EU in 2022, accounting for 16% of the total greenhouse gas (GHG) emissions of the food system (FoodDrinkEurope, 2024).

Economic Viability: Small and medium-sized farms struggle to compete with large agribusinesses that benefit from economies of scale and advanced technologies. This has led to the closure of thousands of small farms each year, forcing many farmers to seek alternative sources of income or leave the sector entirely (The Guardian, 2024). Moreover, inefficiencies in supply chains and an unequal distribution of economic benefits further exacerbate financial instability in the sector (FoodDrinkEurope, 2024).

Social Inclusivity: Food security, nutritional disparities, and rural livelihoods continue to be impacted by market price fluctuations and increasing competition from non-EU imports. Recent farmer protests across Europe have highlighted deep concerns regarding the sustainability of European agriculture under new regulatory frameworks and trade policies (Finger et al., 2024). These tensions emphasize the need for policy adjustments that ensure fair market conditions and equitable support for farmers.

Technological Adaptation: Digitalisation, artificial intelligence (AI) adoption, and data interoperability are being explored to optimize food production and distribution processes. However, significant data gaps remain, particularly in the food transformation and consumption phases, limiting the full potential of evidence-based decision-making (European Commission, 2024). The recent launch of the EU Food System Monitoring Dashboard aims to bridge these gaps by providing policymakers with real-time insights into key trends and risks (Joint Research Centre, 2024).

2.2 Actors in the Food System

The food system is a complex web of interactions and interdependencies, comprising a diverse array of actors each playing a unique role in shaping its structure, function, and outcomes. These actors can be broadly categorized into primary and secondary groups, based on their direct involvement in core processes such as production, consumption, and policymaking (Figure 3). Understanding the roles, responsibilities, and relationships of these actors is crucial for analysing the dynamics of the food system and identifying leverage points for positive change.

2.2.1 Primary Actors

These actors are directly engaged in the fundamental activities of the food system, from producing raw materials to consuming finished products.

Farmers/Producers: Farmers and agricultural producers form the foundation of the food system. They are responsible for cultivating crops, raising livestock, and managing natural resources to generate the raw materials that feed the world. Their decisions regarding what to produce, how to produce it, and the technologies they employ have far-reaching implications for environmental sustainability, food security, and rural livelihoods. Digitalisation efforts, such as data literacy programs, aim to improve farming practices. The role of farmers is evolving with the emergence of new technologies and production methods, with transformations from hierarchical to horizontal structures potentially improving the sustainability of regional food systems. The SOSFood project recognizes the importance of primary producers, planning to include them in multi-actor networks to ensure proposed solutions adapt to their needs.

Consumers: Consumers are the end-users of the food system, whose choices, preferences, and behaviours ultimately drive demand and influence production practices. Their purchasing decisions, dietary habits, and awareness of sustainability issues shape the types of food that are produced, how they are distributed, and the environmental and social impacts of the food system. Increasing consumer awareness, facilitated by improved access to information such as eco-healthy fingerprinting, can drive demand for more sustainable and healthier food options. Projects like SOSFood aim to empower consumers to make informed and sustainable choices through mobile apps providing suggestions on fairer, healthier, and more sustainable options. Understanding consumer food preferences and promoting healthy diets are key components of initiatives aimed at improving public health.

Policymakers: Policymakers at local, regional, national, and international levels play a critical role in shaping the food system through regulations, subsidies, trade agreements, and other interventions. Their decisions can influence everything from agricultural production practices and food safety standards to market access and consumer affordability. Effective policymaking requires a holistic understanding of the food system and its complex interactions, as well as consideration of diverse stakeholder interests and potential trade-offs. The SOSFood project intends to develop policy recommendations in collaboration with researchers and end-users to address knowledge gaps in food system sustainability.

2.2.2 Secondary Actors

These actors indirectly influence the food system by providing essential services, knowledge, and resources to primary actors.

Technology Providers: Technology providers develop and disseminate innovations that transform agricultural production, food processing, distribution, and consumption. These may include companies that manufacture farm equipment, develop digital platforms for supply chain management, or create new food processing technologies. The role of technology providers is becoming increasingly important as digitalisation and automation reshape the food system, influencing factors such as information flow and the diffusion of new technologies. The SOSFood project includes partners specializing in AI technologies and software development to create innovative solutions for data-driven analysis of food systems.

Researchers: Researchers in academia, government, and industry generate new knowledge about the food system, conduct experiments, and develop sustainable solutions. Their work informs policy decisions, guides technological innovation, and promotes sustainable practices across the food system. Research is needed to assess the usefulness of concepts and theoretical perspectives for unveiling the power-digitalisation relationship. The SOSFood project emphasizes the collaboration between researchers and end-users to develop policy recommendations and co-design solutions.

Non-Governmental Organizations (NGOs): NGOs advocate for policy changes, promote sustainable practices, and empower marginalized communities within the food system. They play a critical role in raising awareness of environmental and social issues, mobilizing public support for sustainable solutions, and holding governments and corporations accountable for their actions. NGOs are key stakeholders that should be engaged to bridge gaps and address sustainability.

The SOSFood project includes the participation of NGOs to represent consumers and ensure the solutions proposed adapt to their needs.

Data Experts: Data experts are essential in the digital transformation of the food system, providing the means to collect, analyse, and interpret data to improve decision-making and efficiency. They work on creating data spaces and platforms for data sharing, ensuring data governance and protection. The SOSFood project includes data experts responsible for data management and exploration of new data sources to be added to the Agrifood data space.

Sustainability Experts: Sustainability experts assess the environmental and social impacts of food systems and develop strategies for promoting sustainability. They use methods such as life cycle assessment to quantify impacts and identify areas for improvement. The SOSFood project includes sustainability experts who will study the impact of external elements on the food industry and develop innovative solutions to improve nutrition and health status for all types of consumers.

The interactions and relationships among these primary and secondary actors determine the overall performance of the food system. Understanding their roles, motivations, and power dynamics is essential for designing effective policies and interventions that promote sustainability, resilience, and equity. Projects like SOSFood aim to foster collaboration among these diverse actors to create a more integrated and sustainable food system.

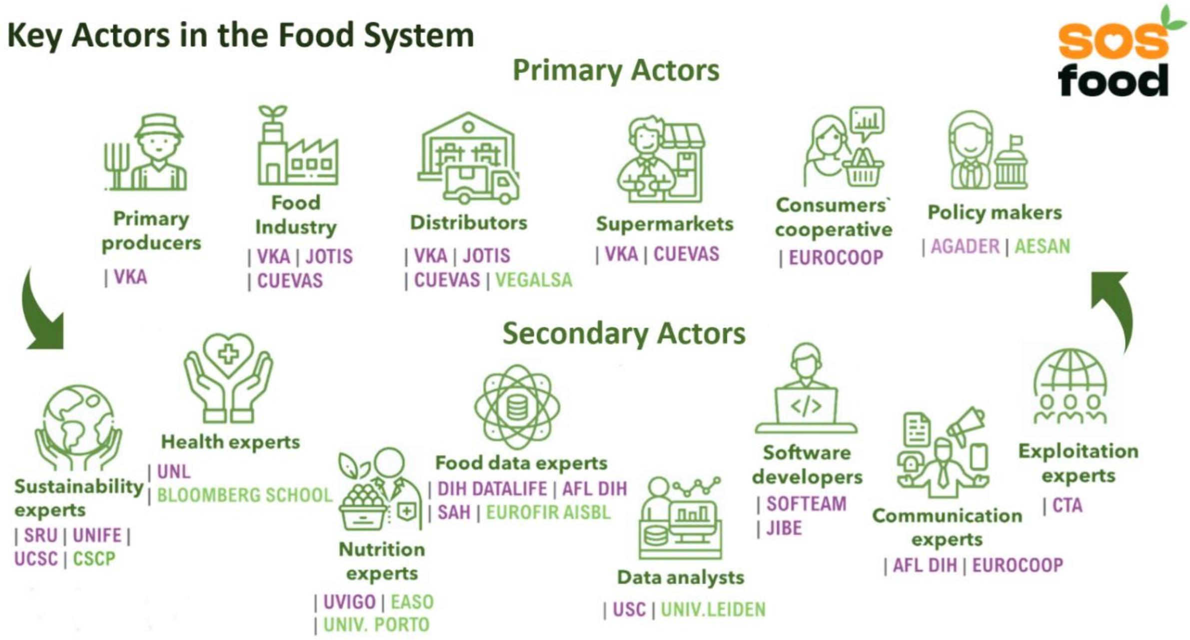

Figure 3. Key actors involved in the SOSFood project

2.3 Food System Boundaries

Defining the boundaries of a food system is essential for understanding its structure, dynamics, and the interactions among its components. These boundaries are influenced by various factors, including geographical and economic constraints, as well as policy and regulatory frameworks (Figure 4).

2.3.1 Geographical and Economic Constraints

Geographical boundaries delineate the spatial extent of a food system, encompassing the areas where food is produced, processed, distributed, and consumed. These boundaries are influenced by factors such as climate, soil fertility, water availability, and infrastructure, which determine the types of food that can be produced and the efficiency of distribution networks. Economic constraints, on the other hand, pertain to the financial resources available for food system activities, including production, processing, and distribution. Economic factors such as market access, trade policies, and economic disparities can significantly impact the functioning and sustainability of food systems. For instance, economic disparities can lead to unequal access to resources and markets, affecting the availability and affordability of food (van Berkum, 2021). Furthermore, the globalization of food markets has increased connectivity and interdependence among countries, facilitating trade but also heightening the vulnerability of food systems to external shocks. For instance, disruptions in global supply chains—due to economic crises, conflicts, or pandemics—can significantly affect food availability and affordability, particularly in regions heavily reliant on imports.

2.3.2 Policy and Regulatory Frameworks

Policy and regulatory frameworks establish the rules and guidelines that govern food system activities. These frameworks include national and international policies on agriculture, trade, food safety, and environmental protection. They play a crucial role in shaping food production practices, influencing consumer choices, and determining the sustainability of food systems (Dornelles et al., 2022). For example, policies that promote sustainable agricultural practices can lead to more resilient food systems, while trade policies can affect the availability and diversity of food products. The Food and Agriculture Policy Decision Analysis (FAPDA) initiative by the Food and Agriculture Organization (FAO) collects and disseminates information on food and agriculture policy decisions, highlighting the importance of policy frameworks in food system governance (www.fao.org/in-action/fapda/fapda-home/en/).
Understanding these boundaries is crucial for developing effective strategies to enhance food security, sustainability, and resilience. By examining the geographical, economic, and policy-related factors that define food system boundaries, stakeholders can identify leverage points for intervention and design policies that promote sustainable and equitable food systems.

Figure 4. Food system boundaries

2.4 The Role of Sustainability

As the global population increases, food demand is projected to grow by 35—56% by 2050 (van Dijk et al., 2021). To reduce the environmental harm caused by current food systems, it is essential to shift towards more sustainable production and consumption practices. Achieving the Sustainable Development Goals (SDGs) involves moving towards sustainable food systems, informed by circular economy principles and an understanding of the interconnected roles of various stakeholders (Polyportis et al., 2024). Growing awareness of the environmental and social challenges associated with food production is driving a transition towards more sustainable practices, such as agroecology, organic agriculture, and circular economy models. However, the shift towards critical changes in sustainable food consumption is progressing at a slow pace (Schulze, Janssen, & Aschemann-Witzel, 2024).

2.4.1 The Three Dimensions of Sustainability

Sustainability is a multidimensional concept that encompasses environmental, economic, and social aspects, all of which must be balanced to achieve long-term resilience and well-being (Purvis, Mao, & Robinson, 2019).

The environmental dimension focuses on preserving natural resources, reducing pollution, and mitigating climate change to ensure that ecosystems remain viable for future generations. According to Rockström et al. (2009), humanity has already exceeded several planetary boundaries (Figure 5), particularly in biodiversity loss, climate change, and nitrogen cycle disruptions. These transgressions threaten the resilience of ecosystems and highlight the urgent need for sustainable agricultural practices, waste reduction, and the promotion of renewable energy sources. Staying within planetary boundaries is crucial for maintaining the ecological balance that underpins food production and human well-being.

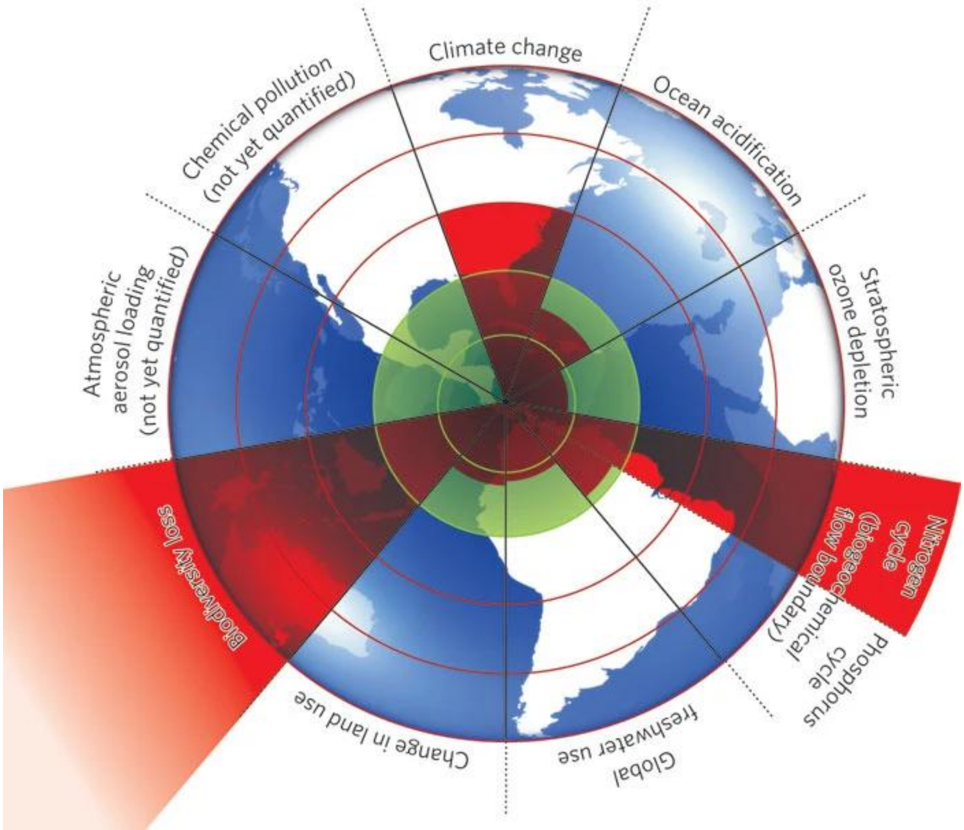

Figure 5. Beyond the boundary. The inner green shading represents the proposed safe operating space for nine planetary systems. The red wedges indicate the current position for each variable. The boundaries of three systems—rate of biodiversity loss, climate change, and human interference with the nitrogen cycle—have already been exceeded. From Rockström et al. (2009).

The economic dimension involves creating resilient and efficient economic systems that can support long-term prosperity. In agriculture and food systems, this means increasing productivity without depleting natural resources, ensuring fair market access, and reducing dependency on environmentally harmful subsidies. Strategies such as precision agriculture and circular economy principles—which emphasise resource efficiency and waste minimisation—can contribute to more sustainable economic models (Foley et al., 2011).

Lastly, **the social dimension** emphasises equity, human rights, and community well-being. It involves ensuring access to education, healthcare, and decent work, while also promoting social inclusion and justice (Dempsey et al., 2011). True sustainability can only be achieved when these three dimensions are integrated, fostering a system that is not only economically viable but also socially just and environmentally responsible.

2.4.2 Indicators of Sustainability

Sustainability indicators in the food system are essential tools for assessing environmental, social, and economic impacts while guiding policies and practices towards more resilient and equitable food production and consumption. Environmental indicators include metrics such as greenhouse gas emissions, water and land use efficiency, biodiversity loss, and soil health. These indicators help evaluate the ecological footprint of agricultural practices and food supply chains, promoting regenerative and climate-smart solutions. Social sustainability indicators assess aspects such as food security, nutrition, labour rights, and fair-trade practices. They highlight disparities in food access, the working conditions of farmers and food industry workers, and the extent to which food systems support equitable livelihoods. Economic indicators measure the affordability and stability of food prices, market access for small producers, and the financial viability of sustainable agricultural models. Additionally, governance-related indicators track regulatory frameworks, policy effectiveness, and stakeholder engagement in decision-making processes. A holistic approach that integrates these indicators allows for a comprehensive understanding of food system sustainability, facilitating data-driven strategies to mitigate risks, enhance resilience, and ensure long-term food security for future generations.

The European Commission has developed several tools to monitor and promote the sustainability of the food system by assessing environmental, social, and economic factors. One of the key instruments is the Agri Sustainability Compass (Figure 6), an interactive tool developed to monitor and visualize the sustainability of agriculture across the European Union. This tool offers a detailed overview of 20 key indicators categorized into three sustainability dimensions: economic, social, and environmental.

Figure 6. Agri Sustainability Compass. Overview of 20 key indicators for the three dimensions of sustainability in agriculture. The economic dimension is shown in blue, the social dimension in yellow, and the environmental dimension in green. From the official [Agri Sustainability Compass](#) website.

Economic Indicators:

1. **Trade Balance** — Measures EU agricultural competitiveness globally.
2. **Agricultural Productivity** — Reflects output efficiency.
3. **Farmers' Income** — Compares farmer earnings with average wages.
4. **Net Value Added per Worker** — Tracks labour productivity over time.
5. **Farm Size and Numbers** — Shows structural change in agriculture.
6. **Value Added in Agriculture and Food Chain** — Highlights economic value within the sector.

Environmental Indicators:

1. **Farmland Birds Index** — Monitors biodiversity on agricultural land.
2. **Crop Diversity at Farm Level** — Measures crop variety for soil health.
3. **Farming Intensity** — Tracks input-intensive farming practices.
4. **Nitrates in Groundwater** — Examines water quality from farming activities.
5. **Pesticides Risk Indicator** — Assesses pesticide risk in agriculture.
6. **Organic Agriculture Land Share** — Reflects growth in organic farming.
7. **Ammonia Emissions** — Monitors ammonia pollution from agriculture.
8. **Greenhouse Gas Emissions** — Tracks emissions from the sector.
9. **GHG Emissions per Euro Produced** — Shows efficiency in terms of GHG emissions.

Social Indicators:

1. **Antibiotic Use per Animal** — Tracks antibiotic consumption in farming.
2. **Farm Manager Age Distribution** — Highlights generational renewal in farming.
3. **Farm Management by Women** — Monitors gender equality in farm management.
4. **Training of Farm Managers** — Tracks educational levels among farmers.

5. **Poverty Rate in Rural Areas** — Compares poverty in rural vs urban areas.

This interactive tool allows users to explore and understand the dynamics of agricultural sustainability in the EU, supporting informed decision-making and targeted strategies for continuous improvement in the sector.

Another important tool is the [EU Food System Monitoring Dashboard](), a tool designed to assess the sustainability of the EU's food system across three key dimensions: environmental, economic, and social. It includes 44 indicators that reflect various aspects of the food supply chain, from agricultural production to consumption. These indicators encompass topics such as food security, resource efficiency, climate impacts, biodiversity, food affordability, public health, and consumer behaviour (Figure 7). The dashboard aims to support evidence-based policymaking by offering a comprehensive overview of the state of the EU's food system and identifying trends and challenges. In comparison, the Agri Sustainability Compass focuses specifically on agriculture, assessing economic productivity, farmer income, and environmental degradation with a more specialized set of indicators.

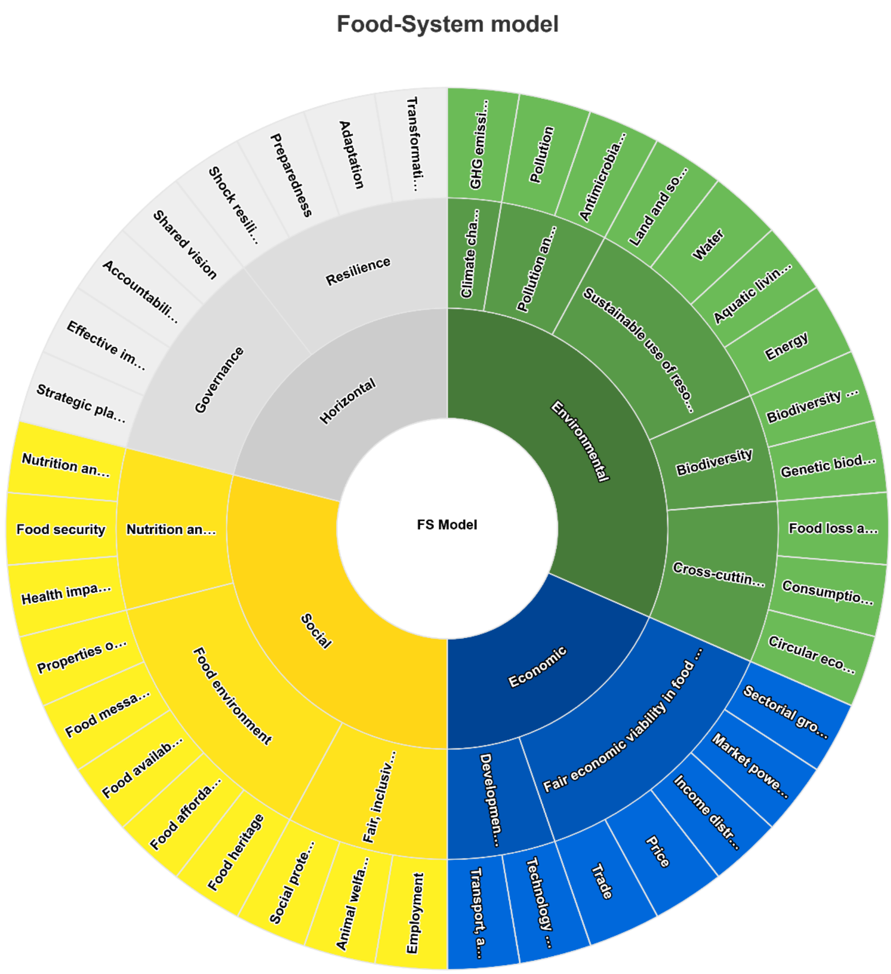

Figure 7. Food-system Model. Overview of the distribution of indicators across sustainability dimensions, thematic areas and domains. From European Commission et al. (2024) and the official [EU Food System Monitoring Dashboard]() website.

The *EU overview* section of the *EU Food System Monitoring Dashboard* provides an interactive visualization of various indicators related to the sustainability of the food system across European countries. Indicators are categorized according to the three dimensions of sustainability—economic, environmental, and social (Figure 8.a)—and can also be grouped by supply chain components for a more detailed analysis (Figure 8.b). Users can explore data at the national level and visualize results through multiple formats, including maps, bar charts, timelines, and tables (Figure 8.c). This interactive tool allows for a comprehensive comparison of indicators across countries and different stages of the supply chain, offering valuable insights into the overall performance and sustainability of the EU food system. Additionally, the *Country Profile* section enables users to compare different nations by selecting countries and analysing their performance across the same set of indicators. This section provides a side-by-side comparison of national data, facilitating an in-depth assessment of differences and trends between EU member states.

Figure 8. EU overview.
a. Indicators categorized by the three dimensions of sustainability.
b. Indicators grouped by both the three dimensions of sustainability and the supply chain component.
c. Example of the GHG food system emissions indicator — bar chart view.
Retrieved from the official [EU Food System Monitoring] page (EU overview section).

By integrating these tools, policymakers, researchers, and stakeholders can gain a holistic understanding of the EU food system's sustainability performance. The combination of the *Agri Sustainability Compass* and the *EU Food System Monitoring Dashboard* provides a robust framework for tracking progress, identifying challenges, and implementing targeted strategies to enhance sustainability. These data-driven approaches support informed decision-making, ensuring that agricultural and food policies align with long-term environmental, economic, and social sustainability goals. As the EU continues to refine its sustainability strategies, such monitoring frameworks will play a crucial role in fostering a resilient, fair, and resource-efficient food system for future generations.

2.4.3 Sustainability and Consumer Choices: A Dynamic Interplay

In the food system, consumer choices and sustainability are intrinsically linked by a dynamic and reciprocal relationship. On the one hand, individual consumer decisions, aggregated into market demand, exert significant pressure on the food system, shaping which foods are produced, how they are cultivated, with what resources, and with what environmental and social impacts (Meybeck & Gitz, 2017). For example, a growing preference for organic products or those derived from circular agriculture can encourage food system operators to invest in such practices and increase their availability (Herrera et al., 2025). On the other hand, the food system itself structures the set of options available to consumers through factors such as product availability, pricing, marketing strategies, access to information, and retail infrastructures (Meybeck & Gitz, 2017).
As highlighted by Halicka et al. (2025) in their study on Generation Z in Poland, awareness of the environmental impact of food choices can differ from awareness of health impacts, influencing purchasing priorities (Halicka et al., 2025). However, by providing clear information on the characteristics of sustainable production systems, such as circular agriculture, it is possible to positively influence consumers' willingness to pay for such products (Herrera et al., 2025).
Furthermore, point-of-sale interventions, such as price adjustments or the introduction of environmental and health labels, can actively steer consumers toward healthier and more sustainable choices. Hoek et al. (2017) found that point-of-sale interventions significantly influenced consumer choices, with price reductions, logos, and informational labels increasing the likelihood of selecting healthier and more sustainable food options. Price variations had the strongest effect, when sustainable options were cheaper, consumers were more likely to choose them. Logos and labels also played a role, but their impact varied depending on the product category and consumer awareness. Consumers responded most positively to combined health and environmental labels, particularly for plant-based meat alternatives. However, some consumers remained resistant to change, even when provided with price incentives or information. The study also revealed that higher subjective knowledge about health and sustainability correlated with a stronger preference for sustainable choices (Hoek et al., 2017). The findings suggest that a multi-faceted approach, combining pricing strategies, clear labelling, and educational campaigns, is most effective in guiding consumers toward sustainable food choices. These insights can inform government policies and industry marketing strategies to promote environmentally responsible diets.
In fact, Ran et al. (2022) delve into the critical role of information as a tool to enhance consumers' capacity, opportunity, and motivation to make more sustainable food choices (Ran et al., 2022). Consumers rely on various sources of information at different stages of their purchasing decision process, underscoring the importance of targeted communication strategies (Ran et al., 2022).
Finally, advancing toward more sustainable diets requires a deep understanding of the multiple economic, social, and cultural factors that drive food choices, recognizing that diets are both a goal and a driving force of sustainable food systems (Meybeck & Gitz, 2017). The historical perspective provided by Upright (2023) further illustrates how increasing consumer demand for sustainable food has shaped the market, albeit with inherent complexities and trade-offs (Upright, 2023).
To foster sustainability in the food system, an integrated approach is essential—one that simultaneously considers consumer education and information to promote more conscious choices, as well as structural and policy changes that make sustainable options more accessible, affordable, and desirable for all (Meybeck & Gitz, 2017; Ran et al., 2022).

2.5 Digitalisation and AI Technologies

2.5.1 Applications in Food System Dynamics

The configuration of the food system is undergoing a profound transformation, driven by factors such as digitalisation, sustainability concerns, and the need for greater efficiency (Raheem, Shishaev, & Dikovitsky, 2019; Sodano, 2024). Digitalisation is reshaping the food system in two main ways: extensively, by improving traditional processes through information and communication technology (ICT), and intensively, by restructuring processes and promoting horizontal peer-to-peer (P2P) interactions (Raheem, Shishaev, & Dikovitsky, 2019). This shift from hierarchical to horizontal structures can enhance the sustainability of regional food systems, making them more responsive to the needs of actors and extending their reach across regions and borders (Jablonski, Schmit, & Kay, 2016).

Several elements contribute to this evolving configuration:

- **Data and Technology**: The use of data and technology, including Artificial Intelligence (AI) and Machine Learning (ML), is central to creating a more productive, inclusive, sustainable, and resilient food value chain. Data exploitation and AI technologies can provide a comprehensive view of the European food system and support stakeholders in making informed decisions.
- **The Internet of Food (IOF)**: This concept encompasses how digital aspects, technical innovation, and new data layers are changing the global food system. It involves considerations such as the complexity of combined food products, their mobility, quantified food handling practices, Big Data, hygiene factors, environmental control through open reporting sensors, self-configuring sensor networks, edible sensors, and multicast instructions.
- **Knowledge Base Creation**: Digitalisation enables the creation of knowledge bases that collate information on foods and food ingredients, making it accessible to customers and users. This involves summarizing information and presenting it in visually impressive formats, such as ontologies or formalized concept systems, to ensure clarity and accuracy.
- **Multi-Actor Networks**: The configuration of the food system increasingly involves multi-actor networks that promote transparency and data sharing across the food system. These networks collect data from various systems (social, political, legal, economic, technological, food, health, environmental, and climate) and co-design solutions in the form of decision-making tools tailored to different users (producers, consumers, policymakers).
- **Sustainability Transitions**: The transition towards sustainable agri-food systems (AFS) is a key focus, balancing food security, environmental security, and social welfare for current and future generations. This involves analysing transitions using frameworks like the multi-level perspective (MLP), which considers niches, regimes, and landscapes (Elsner, Herzig, & Strassner, 2023).
- **Consumer Engagement**: Engaging consumers in the transformation of the food system is vital. Tools like mobile apps can provide suggestions on fairer, healthier, and more sustainable choices, promoting informed purchasing decisions.

The configuration of the food system is also influenced by the need for systemic change that encourages food and nutrition security (FNS) and sovereignty. This involves cross-border collaboration, efficient resource management, and addressing socio-economic challenges such as digital inequality, cybersecurity, and data governance. The implementation of Information

Technology (IT) in the food supply chain requires interdisciplinary cooperation between data scientists, IT personnel, engineers, and stakeholders to create an integrated system from farm to fork (Papastratis et al., 2024). Generative AI, for instance, has the potential to provide information through chatbots and create visual content, but its application in food systems is still in the initial stages.

Overall, the configuration of the food system is moving towards a more digitalized, sustainable, and interconnected model, but it requires careful attention to power dynamics, ethical considerations, and the need for inclusive and equitable solutions.

2.5.2 Challenges and Opportunities of Agri-Food Digitalisation: A Socio-Cyber-Physical Perspective

Digitalisation is not merely a technological process but a broader transformation encompassing social, environmental, and economic aspects. It is crucial to view digitalisation not just as "digitization", the simple conversion of analogic processes into digital formats, but as a profound transformation of business models and interactions among system actors. In this context, the concept of Socio-Cyber-Physical Systems (SCPS) becomes particularly relevant (Metta et al., 2022).

An SCPS acknowledges that agri-food systems are complex and interconnected, involving not only digital technologies (such as sensors, IoT, AI, and blockchain) but also people, communities, and the environment (Calinescu, Cámara, & Paterson, 2019). Unlike traditional Cyber-Physical Systems (CPS), which focus primarily on the integration between physical and computational components, an SCPS explicitly considers the social dimension, recognizing that digital technologies can significantly impact power dynamics, resource distribution, and democratic participation.

By integrating the SCPS perspective, it is possible to analyse how digitalisation affects food systems, taking into account the interactions between technology, environment, and society. This approach allows for the identification of not only the potential benefits of digitalisation (such as increased productivity and waste reduction) but also the risks and challenges, such as inequality in access to technologies, loss of farmers' autonomy, and the concentration of power in the hands of a few actors. Therefore, adopting an SCPS approach is essential to ensure that the digitalisation of the food sector is guided by the common good and contributes to creating more equitable, sustainable, and resilient food systems.

Moreover, for effective and sustainable digitalisation, it is essential to consider the specific context in which technologies are implemented. This means adapting digital solutions to the needs and characteristics of different food system realities, taking into account ecological, social, and organizational specificities. In this way, digitalisation can become a driver of inclusive and participatory development, capable of valuing local knowledge and promoting bottom-up innovation.

2.5.3 Digitalisation Outcomes: Potential Benefits and Risks

Digitalisation is playing a transformative role in the food system, offering innovative solutions to enhance efficiency, sustainability, and competitiveness. However, it also introduces challenges that require careful consideration to ensure an equitable and sustainable transition.

Potential Benefits of Digitalisation

- **Enhanced cost efficiency and market competitiveness:** Automation and data analytics streamline operations, reducing waste, lowering production costs, and increasing profitability. Additionally, digital tools enable small and medium-sized enterprises (SMEs) to access global markets, improving their competitiveness and expanding their customer base in the digital economy (Sridhar et al., 2023).

- **Optimised resource use and waste reduction:** Digital technologies, including precision agriculture and smart monitoring systems, facilitate real-time data collection, allowing farmers to make informed decisions on water, fertiliser, and energy use. These tools help minimise environmental impacts and improve operational efficiency, leading to long-term cost savings (Shamshiri et al., 2024). Additionally, platforms such as the European Commission's Agri Sustainability Compass provide valuable insights into the progress of sustainable food production by consolidating key indicators across economic, environmental, and social dimensions (Agri Sustainability Compass).
- **Job creation and innovation:** Investment in digital technologies promotes employment in high-skilled sectors such as data science, programming, and digital marketing. Moreover, digitalisation supports innovation by enabling the development of new products, business models, and supply chain improvements, fostering long-term economic growth (MacPherson et al., 2022).
- **Improved communication and data sharing:** Digitalisation fosters greater transparency and efficiency within the food system by facilitating data sharing among farmers, agronomists, policymakers, and consumers. This interconnectedness helps align efforts toward sustainability goals and supports the adoption of best practices in the food sector.

Potential Risks of Digitalisation

- **Economic inequality and job displacement:** While automation increases efficiency, it also reduces the demand for low-skilled labour, leading to job losses and widening socio-economic disparities. Without appropriate policies, digitalisation may disproportionately benefit large corporations while leaving smaller enterprises and workers behind (Keogh et al., 2020). Additionally, the high costs of digital infrastructure pose a substantial challenge for small-scale producers, who may struggle to afford the necessary investments for digital transformation, further exacerbating inequalities (Hackfort, 2021).
- **Information asymmetry and power imbalances**: Digitalisation can exacerbate disparities in access to data and market information, disadvantaging small-scale farmers and consumers. Large agribusinesses and tech companies may control key digital platforms, leading to unfair market dynamics and reduced transparency in the food supply chain (Krupitzer & Stein, 2023). Furthermore, concerns about data privacy and ownership arise as farmers risk losing control over their agricultural data, which could be exploited by third parties for commercial gain without adequate compensation or consent (Brunori, Bacco, & Rolandi, 2022).
- **Market disruption and dependence on technology:** Rapid technological advancements can destabilise traditional market structures, making it harder for businesses that are slower to adapt. Additionally, an over-reliance on digital systems creates vulnerabilities—technical failures, cyberattacks, or service disruptions could halt production and supply chains, resulting in economic losses (Montenegro de Wit & Canfield, 2024).
- **Environmental sustainability concerns:** While precision agriculture aims to optimise resource use, it may also lead to a rebound effect, where increased efficiency results in intensified production, potentially worsening environmental degradation (Clapp & Ruder, 2020). Additionally, digitalisation contributes to electronic waste (E-waste) and increased energy consumption, particularly from data centres, IoT devices, and AI-driven systems.

The production and disposal of digital devices pose significant sustainability challenges (Jain et al., 2023).

- **Impact on sustainability goals:** The digital transition in the food sector may not always align with sustainability objectives. On one hand, it enables efficient resource management and emission reductions; on the other, unequal access to digital innovations can exclude small producers from adopting green technologies. Moreover, digitalisation's high energy demand and the production of short-lifespan digital devices could undermine broader sustainability efforts. Ensuring that digitalisation contributes to environmental and social sustainability requires inclusive policies, responsible resource management, and equitable access to digital tools.

While digitalisation has the potential to revolutionise the food system, it is crucial to address its socio-economic and environmental challenges. Without inclusive policies, equitable access to technology, strong data governance frameworks, and environmental safeguards, digitalisation may reinforce inequalities, disrupt markets, and generate unintended sustainability trade-offs. A balanced approach is necessary to ensure that digital transformation supports economic growth, social equity, and environmental responsibility in the food sector.

Table I. Potential Benefits and Risks of Digitalisation in the Food System Across Sustainability Dimensions

Sustainability Dimension	Potential Benefits	Potential Risks
Environmental	**Optimised resource use and efficiency** through precision agriculture and smart monitoring (Shamshiri et al., 2024).	**Rebound effect**: increased efficiency could lead to intensified production, worsening environmental degradation (Clapp & Ruder, 2020).
	Reduced food waste via better supply chain tracking and AI-driven monitoring.	**E-waste and energy consumption** increase due to AI, IoT, and data centres (Jain et al., 2023).
	Improved emissions tracking helps meet sustainability targets.	**Over-reliance on digital monitoring** may reduce focus on broader sustainability reforms.
Economic	**Cost efficiency & profitability** via automation and data analytics (Sridhar et al., 2023).	**Job displacement** in low-skilled agricultural sectors due to automation (Keogh et al., 2020).
	Enhanced SME competitiveness through digital market access.	**High infrastructure costs** limit digital adoption for small-scale producers (Hackfort, 2021).
	Innovation stimulation: new business models, agri-tech startups, and logistics efficiency.	**Market disruptions**, making it harder for traditional businesses to compete and adapt (Montenegro de Wit & Canfield, 2024).
Social	**Job creation in tech-driven sectors**: AI, data science, digital marketing (MacPherson et al., 2022).	**Widening inequality**: large agribusinesses benefit more than small-scale farmers (Keogh et al., 2020).
	Improved transparency: digital platforms enable better data-sharing across stakeholders.	**Power imbalances**: large corporations may monopolise agricultural data platforms (Krupitzer & Stein, 2023).
	Supports food security monitoring and crisis response.	**Digital divide**: small farmers may lack access to necessary technologies (Hackfort, 2021).
	Enhanced collaboration on sustainability goals through data-driven policies.	**Information asymmetry**: large agribusinesses and tech companies may control access to critical market and production data, disadvantaging small producers (Brunori, Bacco, & Rolandi, 2022).
		Data privacy risks: farmers risk losing control over their agricultural data, which could be exploited without consent (Brunori, Bacco, & Rolandi, 2022).

2.5.4 The Interplay Between Consumer preferences and digitalisation

The relationship between consumer demand and Agriculture 4.0 is dynamic, reciprocal, and increasingly integral to the transformation of modern food systems. While Agriculture 4.0 provides the technological foundation for enhancing food production and supply chain efficiency, the evolving nature of consumer demand for higher food standards and transparency (Vergères et al., 2024). However, such growing demand represents a risk for greenwashing communication, mainly from retailers and food processors, to gain advantages from higher willingness to pay for sustainable products. Hence, the ability of agriculture 4.0 to reduce asymmetric information along the supply chain remains an unaddressed challenge (Dolgopolova et al., 2022).

Consumers play a central role are no longer passive recipients of agricultural outputs. Instead, they actively shape agricultural production through their preferences, purchasing behaviours, and advocacy for ethical and sustainable practices (Dolgopolova et al., 2022). According to a recent review the Key areas of consumer influence are:

Food Safety and Traceability: Increasing incidents of foodborne illnesses and contamination scandals have heightened consumer awareness around food safety. In response, digital traceability solutions like blockchain are being implemented to reduce asymmetric information along the supply chain and then, ensuring transparency and enhancing trust (Shiraishi et al., 2025).

Health and Nutrition: A growing emphasis on health and wellness has led consumers to make healthy food choices often based on nutritional value. However, a large body of literature has pointed out that beliefs and food environments are drivers of choice before the use of digital solution (Lusk, 2019). For example (Osaili et al., 2023) pointed out that when use of online food delivery apps, fast food dominates and the online food environment is largely perceived as unhealthy, factors such as food price, delivery time, and the presence of vegetables significantly influence consumer choices. In addition, the development of digital tools is pushing producers to adopt precision agriculture practices that optimise inputs and minimise chemical residues.

Sustainability and Environmental Impact: Eco-conscious consumers are demanding that food systems be sustainable, with particular attention to biodiversity and GHG emissions (Crippa et al., 2021). The evolving consumer preferences towards more sustainable food choices call for transformative and sustainable changes of supply chain (Worley et al., 2024).

One of the most transformative elements of Agriculture 4.0 is the capacity to generate and analyse vast amounts of real-time data across the agri-food value chain. Internet of Things (IoT) devices, mobile applications, and cloud-based systems enable continuous monitoring of everything from soil health and crop growth to consumer purchasing trends.

This constant stream of data creates feedback loops between producers and consumers:

Upstream Data Flow: Information about consumer behaviour (e.g., preferences, reviews, market trends) flows back to producers, allowing them to adjust planting schedules, crop varieties, and marketing strategies.

Downstream Transparency: Producers can share production data (e.g., origin, farming practices, carbon footprint) with consumers to enhance brand credibility and build loyalty.

The synergy of these data flows supports more responsive, demand-driven agricultural systems that reduce food waste, improve resource allocation, and align more closely with market needs.

3. Key Points for Participatory Theory Building

Building a participatory theory requires engaging stakeholders in a structured dialogue to co-create knowledge and strategies that address the challenges and opportunities of digital transformation in the food sector. By incorporating diverse perspectives, ranging from small and medium-sized enterprises (SMEs) to policymakers and researchers, we can ensure that digitalisation fosters economic inclusion, resilience, and sustainability.

One possible approach to structuring this participatory process is conducting a SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis. This method allows stakeholders to collaboratively assess the advantages and risks associated with digitalisation, identifying areas where targeted interventions can maximize benefits while mitigating potential downsides. By integrating such an analytical framework, we can develop a more comprehensive and balanced understanding of how digital technologies reshape economic structures and market dynamics.

Based on these considerations, we propose the following key discussion points for engaging stakeholders in the next phase, particularly those involved in the three case studies. These themes aim to explore actionable strategies for an inclusive, resilient, and equitable digital transition:

1. Creating Inclusive Economic Strategies for Digitalisation

Discuss how stakeholders, particularly small and medium-sized enterprises (SMEs), can collaborate to create inclusive strategies that provide access to digital tools and technologies, reducing economic disparities and fostering equitable growth across the food supply chain.

2. Addressing Economic Inequality Through Retraining and Reskilling

Explore how industry leaders, governments, and educational institutions can work together to design retraining and reskilling programs that mitigate the risk of job displacement due to automation and digitalisation and ensure economic inclusion for all workforce sectors.

3. Promoting Public-Private Partnerships for Digital Infrastructure

Investigate how public and private sector actors can collaborate to reduce the high initial costs of digitalisation for SMEs and develop funding models or incentives that make digital infrastructure more accessible, enabling greater economic participation in the digital food economy.

4. Adapting Business Models for Resilience to Economic Disruptions

Explore how businesses in the food system can adapt their models to become more resilient to digital market disruptions and economic instability. This might include diversifying revenue streams, investing in innovation, and adopting flexible business strategies that respond to technological changes.

5. Addressing Information Asymmetry in the Food Sector

Collaborate with stakeholders to develop strategies that bridge the information gap in the food supply chain. Ensuring that all participants, especially small producers and consumers, have access to accurate, timely, and transparent information can promote fairer market practices, enhance trust, and improve decision-making processes across the sector.

6. Investigating Trade-offs among Different Sustainable Dimensions

Digital transformation affects economic viability, environmental protection, and social equity, as technological advancements can enhance efficiency while potentially exacerbating issues like inequality and resource uses.

4. Conclusions

This conceptual framework provides a structured foundation for understanding the complexities of the European food system and the transformative role of digitalisation. By examining the system's configuration, key actors, and sustainability dimensions, we highlight the interconnected challenges that shape food system dynamics. The integration of digital and AI technologies presents both opportunities and risks, requiring a balanced approach to ensure economic viability, environmental responsibility, and social equity. As digital transformation accelerates, careful consideration must be given to its broader systemic implications, particularly in addressing existing inequalities, market power imbalances, and environmental trade-offs.

Sustainability plays a pivotal role in shaping the future of food systems, requiring an integrated approach that balances environmental, economic, and social dimensions. As global food demand continues to rise, ensuring long-term sustainability means not only improving resource efficiency and reducing environmental degradation but also promoting inclusive economic growth and social equity. The concept of sustainability, as explored in this framework, underscores the necessity of moving beyond short-term efficiency gains and towards holistic, system-wide resilience. The use of sustainability indicators—ranging from greenhouse gas emissions and biodiversity loss to economic viability and social inclusion—provides valuable tools for monitoring progress and guiding policy interventions. The EU's initiatives, such as the *Agri Sustainability Compass* and the *Food System Monitoring Dashboard*, demonstrate the importance of data-driven approaches in tracking sustainability performance and identifying key areas for improvement. These tools offer crucial insights that can inform evidence-based policymaking and enhance collaboration among stakeholders.

In the next phase, a participatory theory-building approach will be essential to navigate this transition effectively. Engaging stakeholders—ranging from policymakers and industry leaders to small producers and consumers—will allow for the co-development of strategies that are not only technologically feasible but also socially inclusive and economically viable. Collaborative discussions can help bridge information gaps, foster inclusive economic growth, and promote resilient business models that adapt to digital disruptions while preserving key values of fairness, accessibility, and sustainability. By incorporating analytical tools such as SWOT analysis and leveraging cross-sector collaborations with stakeholders involved in the three case studies, we can create a more structured decision-making process that ensures digitalisation enhances, rather than disrupts, the food system's sustainability and inclusivity.

Future research and policy efforts should focus on refining these frameworks, deepening stakeholder engagement, and developing actionable pathways for a just and efficient digital transformation. This requires a commitment to interdisciplinary approaches that integrate economic, social, and environmental perspectives, ensuring that digital innovations contribute to a more equitable and sustainable food system. Additionally, long-term monitoring and evaluation mechanisms should be established to assess the impacts of digitalisation and guide adaptive policy interventions.

Only through collective action, continuous adaptation, and proactive governance, we can build a resilient food system that meets the needs of diverse actors while addressing long-term sustainability challenges. By fostering collaboration, innovation, and inclusivity, we can harness the full potential of digitalisation to create a more just, efficient, and future-proof food system.

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Funded by
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Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA).

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