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Towards sustainable food systems: developing a monitoring framework for the EU

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Adequate monitoring of the EU transition toward sustainable food systems can promote policy coherence and provide better evidence for informed policy making. This paper presents an initial concept and methodology for an EU food system monitoring framework, integrating a systems' perspective and key sustainability elements relevant to the EU context. Grounded in scientific evidence and extensive dialogues among scientific experts with interdisciplinary backgrounds, we define an EU food system sustainability model that provides a conceptual framework for monitoring. This model encompasses 12 thematic areas and 37 indicator domains, synthetized through a rigorous review of existing frameworks and the assessment of nearly 250 relevant indicators via a transparent workflow and an integrated collaborative digital tool. We identify data gaps that signal challenges ahead in effective monitoring, but also opportunities for research and cooperation. To advance with an EU food system monitoring framework, it is essential to engage in participatory processes with stakeholders, ensuring an inclusive and transparent approach.

KEYWORDS

sustainable food systems, monitoring framework, food policy, EU policy, systems perspective, food chain

1 Introduction

Food systems can play a pivotal role in the balance between preserving our planet and human activities (FAO, 2014, 2018). Achieving sustainable food systems is key for operating within the planetary boundaries, safeguarding the environment, securing the economic viability and resilience of food systems and ensuring wellbeing of current and future generations (Conijn et al., 2018; Springmann et al., 2018; Gerten et al., 2020). At the same time, it is fundamental for progressing toward the Sustainable Development Goals (SDGs) set in the United Nation (UN) 2030 Agenda (UN, 2015) including Zero hunger (SDG2), Good health and wellbeing (SDG 3), Decent work and economic growth (SDG 8), Climate action (SDG 13), Responsible production and consumption (SDG 12), Life below water (SDG 14) and Life on land (SDG 15). These interlinkages were largely discussed during the 2021 Food Systems Summit, which globally enhanced awareness of accelerating progress toward the SDGs (UN, 2021b).

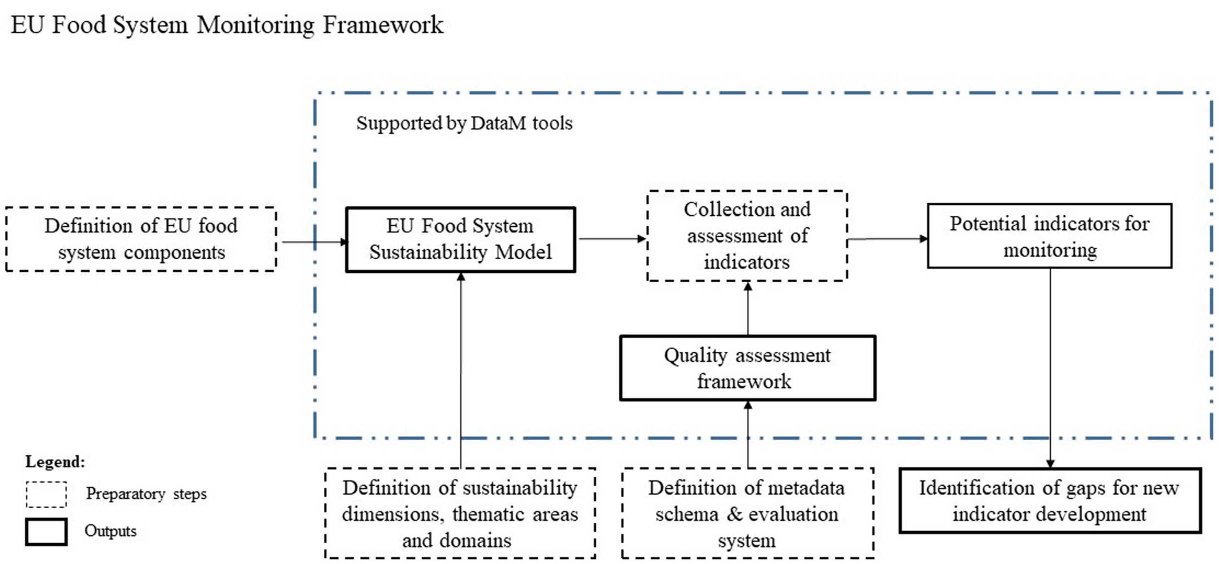

FIGURE 1
Overview of the methodological steps for defining a monitoring framework for the EU food system.

Understanding the complexity of food systems is crucial for effective policy-making (Hebinck et al., 2021; Kugelberg et al., 2021; Marshall et al., 2021) that requires navigating through a web of interconnected actors and activities, influenced by sectorial perspectives and occasionally conflicting interests. Therefore, to track policy impact and foster dialogues (EC, 2020c; Fanzo et al., 2020, 2021; OECD, 2021, 2022), adequate evidence and monitoring the progress become instrumental (Fanzo et al., 2021; Hebinck et al., 2021; Garton et al., 2022 and references therein).

Proposals to monitor food systems have been developed by different authors (Gustafson et al., 2016; Béné et al., 2019; Fanzo et al., 2021; Hebinck et al., 2021), which diverge in perspective, purpose, granularity, and contextualization within the broader socio-economic or environmental conditions. More recently, tools to track food system transformation in the global context became available (Schneider et al., 2023) such as the Food System Countdown Initiative (FSCI)[1] or the Food Systems dashboard.[2]

However, in the EU, no overarching framework to monitor the sustainability of the food system has been established that integrates the views, policies and available monitoring systems in the EU region. The European Commission (EC) and stakeholders have developed several monitoring frameworks that relate to specific components of the food system (e.g. agriculture, fisheries, aquaculture, biodiversity, emissions, agri-food markets, food security) (EC, 2023b, 2023c, 2023f, 2023j; EEA, 2023b; Gras et al., 2023; Kilsedar et al., 2023) and inform on the progress of specific EU policies (EC, 2018a, 2020a; EU, 2021c; EC, 2023d). However, there is no tool with a holistic system perspective to monitor progress and guide decision-making in line with sustainability objectives (EEA, 2023a). The EU's food system strategy "Farm to Fork" (F2F) (EC, 2020c) within the European Green Deal (EC, 2022) was the first attempt to introduce a more integrated approach (Schebesta and Candel, 2020). It highlights the importance of monitoring the transition toward sustainability, including progress on the targets and overall reduction of the environmental and climate footprint of the EU food system.

This paper outlines the development of a framework to monitor the transition of the EU food system toward sustainability, which is grounded in a rigorous review of existing frameworks (Gustafson et al., 2016; Béné et al., 2019; Fanzo et al., 2021; Hebinck et al., 2021) and prior participatory processes (Bock et al., 2022). It also integrates insights from existing sectorial initiatives (EC, 2023b, 2023c, 2023f, 2023j; Gras et al., 2023; Kilsedar et al., 2023) to align with the EU's commitment to policy coherence (EU, 2019a). The objective is to provide an evidence-based proposal that sets the foundation for rigorous monitoring and highlights areas with insufficient data.

2 Methods

Developing a framework to monitor the sustainability of food systems requires a systematic approach, as depicted in Figure 1. This section describes the key methodological steps and assumptions guiding the development of the EU food system sustainability model; collection and assessment of indicators; implementation through the DataM tool (https://datam.jrc.ec.europa.eu/) and identification of areas for new indicator development.

2.1 Development of the EU food system sustainability model

The conceptual foundation of the monitoring framework is the EU Food System Sustainability Model. This model identifies the key concepts, including the components of the food supply chain and economic, environmental and social dimensions, subdivided into thematic areas and domains. This structure serves for anchoring the

1 https://www.foodcountdown.org/
2 https://www.foodsystemsdashboard.org/

indicators to track progress in key areas and provide a basis for monitoring the transition toward sustainable EU food system.

In the first step, the boundaries of the framework were defined by reviewing existing global (CIAT, 2017; HLPE, 2017; Van Berkum et al., 2018; Fanzo et al., 2021) and EU (Zurek et al., 2018; Bock et al., 2022) food system models. This resulted in the overview presented in Figure 2. The food supply chain component follows the concept of life cycle thinking (Castellani et al., 2017), starting from raw material extraction for food production up to waste stream management. The sustainability aspects were distributed across environmental, economic and social dimensions, which is in line with the definition of sustainable food systems by FAO (2018), the EU common practice on Better Regulation (EC, 2023a) and the approach of the Group of Chief Scientific Advisors in the EU (SAPEA, 2020). Governance and Resilience are identified as horizontal thematic areas across all sustainability dimensions that provide metrics and responses to pressures and impacts on the system. The Driver-Pressure-State-Impact-Response (DPSIR) framework (Smeets et al., 1999) integrated in our model constitutes a structure to reveal causal relationships between the drivers (human needs), pressures (human activities), environmental state (negative trends), impacts (cascading social, environmental or economic changes), and responses (institutional policy and programs to improve conservation). It become instrumental in the selection and categorization of the indicators (see section 2.2).

We defined our food system model based on a review of existing food system monitoring frameworks (Gustafson et al., 2016; Béné et al., 2019; Fanzo et al., 2021; Hebinck et al., 2021). Béné et al. (2019) provided a global map of food system sustainability and distributed indicators across four dimensions, including environmental, social, economic, and food and nutrition aspects, with nine sub-dimensions. Fanzo et al. (2021) adapted the food system framework proposed by the High-Level Panel of Experts of the Committee on World Food Security (HLPE), defining five critical thematic areas for monitoring: diets, nutrition and health, environment and climate, livelihoods, poverty and equity, and governance and resilience. Hebinck et al. (2021) suggested a sustainability compass structured around four societal goals and areas of concern, offering sustainability scores derived from progress indicators and performance metrics. Gustafson et al. (2016) outlined seven metrics for sustainable nutrition security, covering nutrition, environmental, economic and social factors, together with resilience, food safety, and waste. These frameworks constitute diverse perspectives of monitoring with a unique objective: to guide the transition of food systems toward sustainability.

To shape the identified elements to the EU context, we integrated the results from prior participatory processes (Bock et al., 2022). The sustainability objectives of the EU food system were defined and aligned with UN SDGs, FAO's definition (FAO, 2014) and the principles outlined in its European adaptation (SAPEA, 2020). These emphasize safe, nutritious, healthy, environmentally friendly food, together with resilience, economic dynamism, fairness, social inclusiveness and global food accessibility without environmental harm. We paid specific attention to analysing EU policies related to food system sustainability, including, among others, the Farm to Fork Strategy, the Biodiversity Strategy, the Common Agricultural Policy and the Common Fisheries Policy. Supplementary Table S1 describes how the UN SDGs, the sustainability objectives of food systems and the key EU policies and strategies are linked to the thematic domains of the EU Food System Sustainability Model.

Mapping EU policies and strategies to the reviewed food system frameworks was essential to highlight the main areas of concern in the

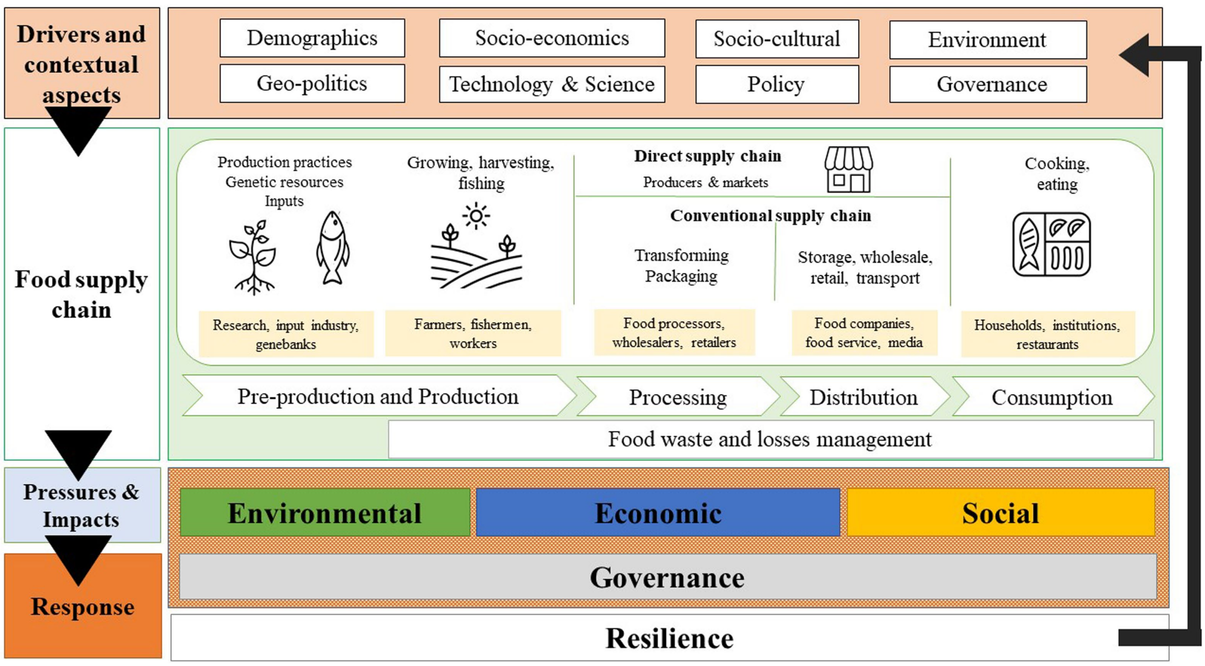

FIGURE 2
EU Food System Sustainability Model - overview.

EU and tune the framework to the EU context. For instance, the circular economy, the consumption footprint and the economic viability of businesses were due to their significance in EU policies. It is important to note that this model also reflects the authors' background, encompassing agriculture, economy, nutrition, social and environmental sciences as well as their experience in providing scientific evidence in policy making. Supplementary Table S2 illustrates how the different sources of information contributed to the proposed Food System Sustainability Model. The proposed model is described in the Results section.

2.2 Collection and assessment of indicators

We collected nearly 250 indicators deemed potentially relevant for the monitoring framework, with thematic area experts overseeing the process and identifying indicators by domain. Following the "re-use of existing" principle (Wilkinson et al., 2016; EC, 2018b) data came from various sources, including EU official data, other data dashboards from EU institutions and agencies, international organizations, and scientific models of the Joint Research Centre (JRC) of the European Commission.

Preserving coherence with other frameworks was challenging due to differing naming conventions and classification systems. To address this, we conducted a detailed analysis to understand the semantics of the possible data sources. We also developed a harmonized metadata profile (Supplementary Table S3) to assess and compare indicators effectively, ensuring consistency across metadata elements. The DPSIR framework was also employed, which ensured that all the casual chain for different impact pathways could be assessed and monitored, thereby understanding better potential changes of cause-effect relationships as well as anticipating potential changes in the short-term (e.g, rising energy demand without a shift to renewables would likely result in increased GHG emissions, highlighting short-term trends).

Based on these metadata elements, we developed a Quality Assessment Framework, where every collected indicator should be assessed against relevance, methodological soundness, geographical coverage, and temporal characteristics (Supplementary Table S4) with the aim to select those that are reliable, have stable and continuous data supply, and ensure internal consistency and balanced coverage across sustainability domains. The assessment of indicators was undertaken by thematic area experts to ensure adequate knowledge was steering this process. This step also revealed areas of insufficient data coverage. Identifying and addressing these gaps is crucial for outlining future work and research priorities. The gaps are further described in section 3.

2.3 Implementation with the DataM platform

The food system monitoring framework can be also defined as an information system. Given the complexity and interdisciplinary nature of food systems, ensuring interoperability is fundamental. To handle the big amount of information, we opted for an early implementation of the system that integrates the data model with the components of the food supply chain and elements of sustainability, the harmonized metadata schema and the Quality Assessment Framework.

The data model harmonized the semantics across the system, which was further supported by standardized code lists (e.g. a list of underpinning policies, food supply chain components, data granularity levels, spatial extent, temporal characteristics, etc). This standardization also supported the automation of several steps in quality assessment of the indicators. For transparency, we provide the full model as a UML (Unified Modelling Language) class diagram in Supplementary Figure S1.

For a successful implementation of the monitoring framework, an IT tool that supports collaboration, access control and system implementation is essential. The DataM tool (EC, 2023e),[3] developed at the JRC, was selected due to its adaptable data schemas, dynamic forms, and integrated data environment. It also supports the entire production cycle, starting from documentation of potential indicators until updating the implemented system. Importantly, this can take place without data storage, enabling real-time retrieval and automated updates from the original data sources to enhance decision-making and operational workflows. These properties directly respond to the FAIR data principles, ensuring that the collected data are Findable, Accessible, Interoperable, and Reusable (Wilkinson et al., 2016; EC, 2018b). The system architecture, illustrated in Figure 3, highlights the database, machine-to-machine communication, and the interfaces for system development, expert utilization, and public communication.

2.4 Identification of knowledge gaps

The last methodological step in the development of the EU food system monitoring framework was to identify areas with knowledge gaps where no or insufficient data are available. Having had linked the indicators to the elements of the data model this step was quite straightforward. With a simple query, the blank areas, where more research and data collection are needed could be defined, as presented in Supplementary Table S6.

3 Results

3.1 Proposed EU food system sustainability model

The proposed EU Food System Sustainability Model encompasses 12 thematic areas and 37 domains across environmental, social, and economic dimensions, including resilience and governance as horizontal thematic areas (shown in Figure 4). This structure serves to anchor the indicators. The following sections describe this model in detail, following its hierarchical structure, and identify areas with knowledge gaps where no or insufficient data are available.

3 https://datam.jrc.ec.europa.eu

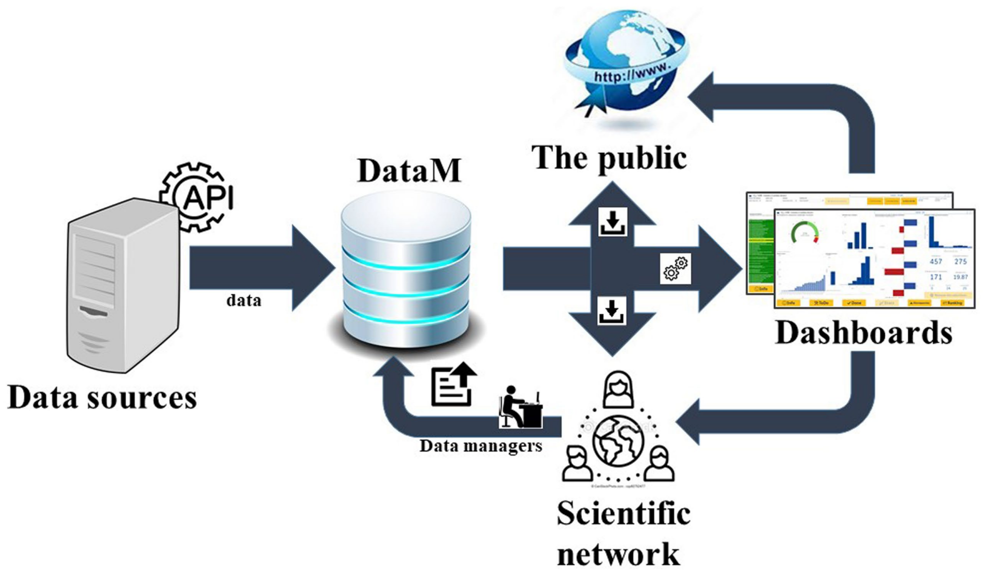

FIGURE 3
IT architecture of the proposed EU food system monitoring framework.

3.2 Thematic areas and domains

This section describes the thematic areas and domains of the EU Food System Sustainability Model (Figure 4), focusing on their relevance to the EU context. The environmental dimension encompasses five thematic areas, highlighting the complex interconnections and the multi-faceted nature of environmental challenges within the food system. Specifically, it addresses climate change, pollution and antimicrobials, sustainable use of resources, biodiversity and other cross-cutting environmental domains. The economic dimension includes two key thematic areas crucial to a secure, resilient and competitive food system in the EU. They focus on the economic viability of businesses across the food value chain, and the development and logistics related to food production and distribution. The social dimension comprises three thematic areas, focusing on fairness and ethics, the food environment and nutrition and health aspects. In addition, governance and resilience have been included as horizontal thematic areas to cover critical interactions steering the development of the food system and inform on its potential to adapt to the challenges of sustainability.

3.2.1 Climate change

This thematic area is central in various food system monitoring frameworks (Gustafson et al., 2016; Béné et al., 2019; Fanzo et al., 2021; Hebinck et al., 2021), and is of international priority (FAO, 2018; UNEP, 2023). In the context of food systems, the EU addressed it in the European Climate Law (EU, 2021b), the Industrial Emissions Directive (EU, 2024a), the strategic plan regulation of the Common Agricultural Policy and synthetising them in the F2F Strategy. Our framework highlights the role of the whole food supply chain in achieving the EU greenhouse gas (GHG) emissions reduction targets, which aim for at least a 55% decrease below 1990 levels by 2030, 90% decrease by 2040 (EC, 2021b), and moving toward a climate-neutral Union by 2050 as outlined in the European Climate Law.

3.2.2 Pollution and antimicrobials

Today's food production, relying heavily on inputs, is a significant contributor to various forms of pollution. They substantially impact environmental integrity and, ultimately, public health (Sala et al., 2023). Addressing pollution requires not only enhancing the efficiency of food systems, but also tackling pollution in absolute terms, i.e., considering the overall contribution of food systems to pollution (Cordella and Sala, 2022). Both the EU (EC, 2020c, 2020b; EU, 2021a) and the UN (FAO et al., 2022) established ambitious reduction targets accentuating the significance of their stringent monitoring, while highlighting the growing environmental and public health concern. Achieving these targets requires quantifying and assessing interventions along the food supply chain and their effect. The two domains of this thematic area address the environmental pollution streaming from applying chemicals and antimicrobial resistance that is associated with the use of antimicrobials in growing food producing animals (Fanzo et al., 2021; Bock et al., 2022).

The *Pollution domain* aims to identify and assess the drivers and effects of the emission of pollutants to the environment along the food chain, with a strong focus on the use of fertilizers and pesticides in EU agriculture. Excessive use of these chemicals often results in environmental contamination, potentially disrupting ecological balances (Sanyé-Mengual et al., 2023). This can contribute to biodiversity loss (Tang et al., 2021), eutrophication (Le Moal et al., 2019), and soil degradation (van der Putten et al., 2023). It should be noted that the 16 impact categories (such as marine and freshwater eutrophication, human and freshwater toxicity, or particulate matter) of the Environmental Footprint method (Sala et al., 2023) assess the impacts of pollution considering the entire life cycle of EU food consumption.

In parallel, the overuse of *antimicrobials* in food production is one of the drivers of antimicrobial resistance (AMR) (Ager et al., 2023), posing a threat to human and environmental health by altering

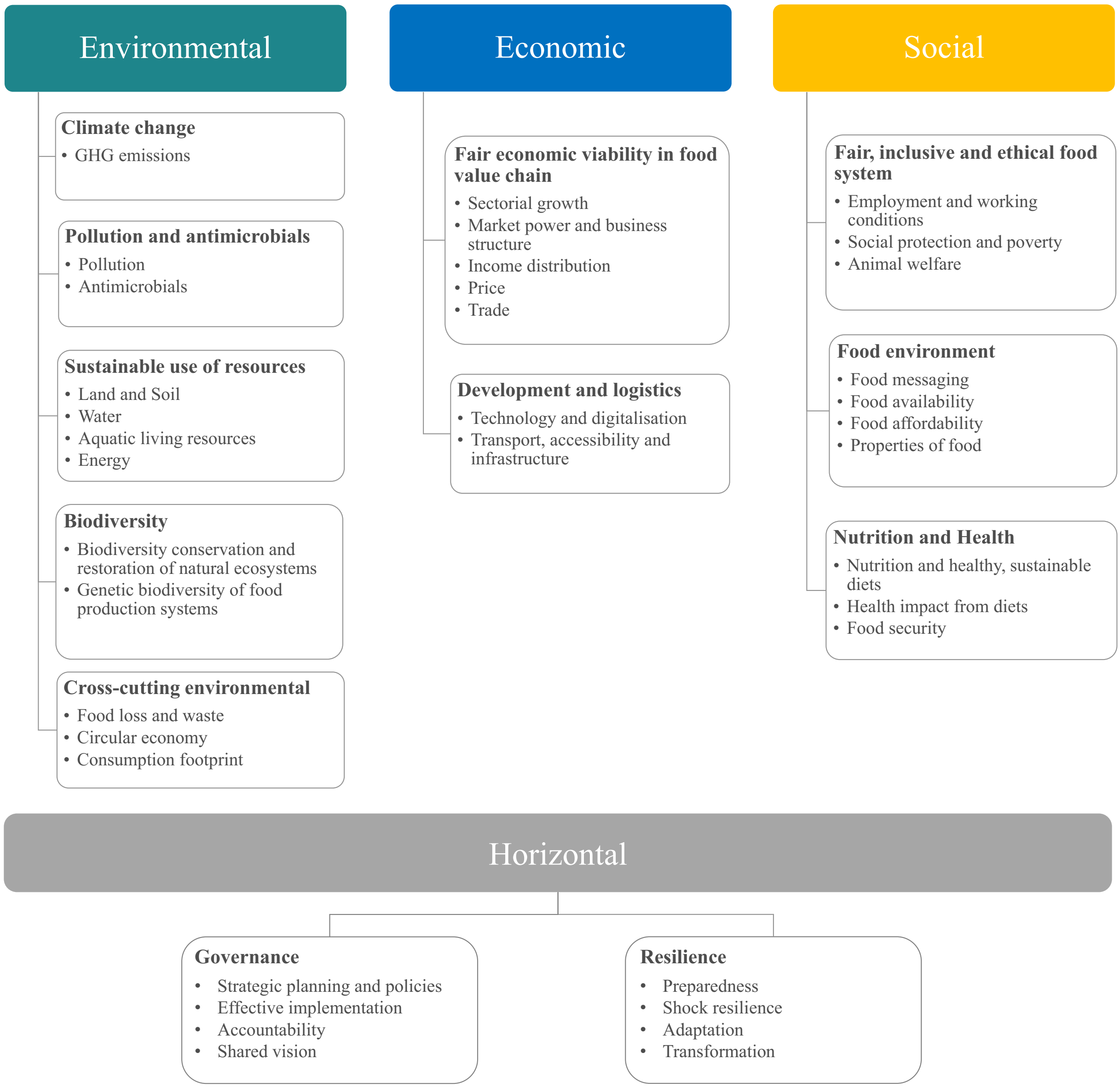

FIGURE 4
Sustainability dimensions, thematic areas and domains of the EU Food System Sustainability Model.

microbial communities in soil and water bodies (Woolhouse et al., 2015).

3.2.3 Sustainable use of resources

Ensuring sustainable *water* use and improving water quality (EU, 2000) are emphasised in existing food system frameworks (FAO, 2018; Béné et al., 2019; Fanzo et al., 2021; Hebinck et al., 2021) and are key within the F2F Strategy (EC, 2020c) and in EU water policies (EU, 2000, 2020). Reusing reclaimed water in agriculture and desalination for irrigation has high potential for enhancing sustainable water use (Galimberti et al., 2020; De Roo et al., 2023). When calculating consumption footprint, it is particularly important to consider the impacts of water use all over the supply chain, including that of imported raw materials to properly account varying water scarcity among the regions (Sala et al., 2023). Water quality often deteriorates because of agricultural practices, such as fertilizer overuse or chemical pesticide use (Mateo-Sagasta et al., 2017), as well as end of life processes (e.g., wastewater treatment). The Consumption Footprint method also measures eutrophication and ecotoxicity (Sala et al., 2023).

Sustainable *land* use and *soil* health is key for long-term land productivity, ecosystem preservation, carbon sequestration and thus, climate change mitigation, and contributing to the UN SDGs (2.4, 15.1). Diverse agricultural systems and practices, such as organic farming, agroforestry, precision farming, crop diversification and crop rotation, contribute significantly to the complexity of land use. Agricultural land is also used for feed and bio-based products, which can raise concerns about balancing with food security (Muscat et al., 2020). These conflicting objectives have a direct impact on trade between EU and non-EU countries (Vera et al., 2022). Therefore, effective land use is key to successfully tackling sustainability challenges (Foley et al., 2005), including climate change (Pongratz et al., 2021), biodiversity loss (Sanyé-Mengual et al., 2023), spread of invasive alien species (Polce et al., 2023), soil productivity (Montanarella and Panagos, 2021) and human health (Zaller et al., 2022).

The EC has set medium-term objectives via its F2F (EC, 2020c) and Biodiversity strategies (EC, 2020d) to increase the area of organic farming (incl. aquaculture) and agricultural land allocated to non-productive features, which are reinforced by the EU Common Agricultural Policy (CAP) (EU, 2021c) through mandatory conditions and agri-environment-climate measures. Concerning the state of soils, around 60–70% of EU soils are not in a healthy state (Panagos et al., 2022; EC, 2023g). The EU Soil Strategy for 2030 (EC, 2021c) aims to protect, restore soils and ensure their sustainable use. The proposed Soil Monitoring and Resilience Law aims to restore major part of unhealthy soils by 2050 (EU, 2023b).

While there is a good snapshot of soil health based on state of the art indicators (e.g., erosion, soil organic carbon, nutrients, diffuse pollution, compaction, sealing), trends are expected by 2030 as more soil monitoring data become available through the outputs of the soil mission projects and data flows from Member States (Panagos et al., 2024). The Consumption Footprint incorporates effects on four soil properties—soil erosion, mechanical filtration, physicochemical filtration, and groundwater regeneration—resulting from land use and land use change linked to the EU food system.

To achieve food system sustainability, *aquatic living resources* [also referred to as the water-based food systems, or 'blue food' (Webb et al., 2023)] are equally important. The main challenge is to reduce the impact of unsustainable aquatic food production practices (Morales-Nin et al., 2024) and aligning with the Common Fisheries Policy (EU, 2013b), the Biodiversity Strategy (EC, 2020d) and the F2F Strategy (EC, 2020c). This is crucial not only for the current generation, but also for the long-term health of marine and fresh water ecosystems.

The F2F Strategy (EC, 2020c) emphasizes the significance of *energy* efficiency and using renewables in all food sectors, aiming to increase green energy production and implement energy-saving solutions across the food chain. This aligns with reducing environmental impact and combatting climate change. EU policies and support measures, such as financial incentives and regulatory frameworks, are already available (EC, 2018a, 2020a; EU, 2023a) to promote renewable energy production in these sectors. Beyond environmental goals, the energy domain also has important economic and social implications, particularly for rural areas, the food industry and transport along the food chain (Monforti-Ferrario et al., 2015).

3.2.4 Biodiversity

Biodiversity, comprising both wildlife and agrobiodiversity, is a commonly included component of indicator frameworks for food-system sustainability (Béné et al., 2019; Fanzo et al., 2021; Hebinck et al., 2021). This is particularly consequent given that global food systems contribute significantly to biodiversity loss (Benton et al., 2021), while relying on ecosystem services (such as pollinators and organic contents in soil) of biodiversity for food security (Tscharntke et al., 2012). When monitoring biodiversity, it is worth considering its relations with other environmental domains, such as pollution or land use. Thus, indicators in these latter domains also provide information on biodiversity (Fanzo et al., 2021).

EU efforts toward sustainable food system are aligned with diverse policies on conservation and restoration of both natural and managed terrestrial and aquatic ecosystems [i.e., Biodiversity Strategy (EC, 2020d), Nature Restauration Law (EU, 2024b), F2F Strategy (EC, 2020c), Common Agricultural Policy (EU, 2021c), Common Fisheries Policy (EU, 2013b), Marine Strategy Framework Directive (EU, 2017)]. The two main EU marine policy instruments contribute to the conservation of marine organisms and associated ecosystems in order to protect biologically sensitive areas. On agricultural land, on the other hand, measures focus on reducing inputs and conserving non-productive elements (i.e. landscape features and semi-natural areas), which are crucial for maintaining biodiversity and the ecosystem services they provide. In addition, the EU recognises the urgency to address biodiversity loss caused by the globalization of the food systems, acknowledging the EU's contribution to global biodiversity loss through climate and global land use change (Sala et al., 2023; Sanyé-Mengual et al., 2023).

Yet, the definition of biodiversity includes not only species variability, but also within-species genetic variation (CBD, 2006). This *genetic biodiversity* is also vital for the provision of ecosystem services and to ensure resilience in food systems. Crop and livestock new varieties and hybrids help maintaining system stability (HLPE, 2012; Rawal et al., 2019). In addition, wild relatives and traditional plant varieties and animal breeds with increased resilience to different types of shocks (e.g. pest damage, drought, heatwaves) are globally recognized as a key biodiversity resource that is also fundamental for the F2F and the Biodiversity strategies.

3.2.5 Cross-cutting environmental domains

In recent years, reducing *food loss and waste* gained an increasing focus, manifesting in SDG target 12.3, aiming to halve the per capita global food waste by 2030 (UN, 2015). Aligning with this objective, the EU set the reduction of food loss and waste as a key priority in the F2F Strategy (EC, 2020c) and the revised Waste Framework Directive (EC, 2023h), where the latter proposes concrete food waste targets. Since 2020, Member States (MS) are obliged to report food waste data by supply chain components (EC, 2008). However, these data have limitations, such as granularity per food groups and products, hindering the identification of major contributors to food waste generation. Completing official data with models provides additional estimates on food loss and waste (De Laurentiis et al., 2021), which could aid in monitoring the progress.

The *Circular Economy* Action Plan (CEAP) (EC, 2020a), a key element of the European Green Deal, aims to facilitate the EU's transition to a circular economy. It targets to reduce pressure on natural resources, foster sustainable growth and create jobs, in line with the EU's 2050 climate neutrality target and halting biodiversity loss. The CEAP focuses on sectors with high resource use, like water and nutrients in the EU food sector, aligning with the SDGs (e.g., SDG12, UN, 2015), the Biodiversity Strategy (EC, 2020d) and the Zero Pollution Action Plan (EC, 2020d; EU, 2021a). Beyond food waste prevention, circular strategies, such as valorisation pathways in food supply chains, can optimize waste flows. With this aim, the EU revised the EU monitoring framework for the circular economy (EC, 2023c).

Understanding the overall environmental impact of the EU food system is crucial for remaining within the planetary boundaries

(Gerten et al., 2020; EC, 2020c). The *Consumption Footprint* indicator developed by the JRC assesses the environmental impacts of EU consumption considering the footprint of food products and processes (Sanyé-Mengual and Sala, 2022; Sala et al., 2023; Sanyé-Mengual et al., 2023). Based on Life Cycle Assessment (LCA), it evaluates the entire life cycle of consumed food products in the EU, from raw material extraction to waste management, including trade impacts with other world regions. The related indicators cover 16 impact categories, which can be assessed against the Planetary Boundaries (Sala et al., 2020) and linked with the SDGs (Sanyé-Mengual and Sala, 2022). The assessment includes all food products and the entire food chain comprising trade, while allowing identifying the potential trade-offs among the environmental impacts. The model was also tested for social (Mancini et al., 2023) and biodiversity footprints (Sanyé-Mengual et al., 2023).

3.2.6 Economic viability of businesses

Ensuring the steady generation and fair distribution of value added is crucial for the economic viability of all businesses and stakeholders in the food chain, thereby enabling *sectorial growth* for all sectors. By assessing the distribution of value added at each step of the food chain, insights can be gained into the fairness and equity of the food system. Businesses in the primary sectors have a higher number, but a comparatively smaller share of value added (Hebinck et al., 2021). Inclusion of value added in agriculture is also acknowledged as an economic sustainability indicator (Béné et al., 2019). Several EU initiatives aim to support primary producers in obtaining a fair share of added value through sustainable production. Derogations from competition rules, or provisions of the Common Agricultural Policy (EU, 2021c), Unfair Trading Practices Directive (EU, 2019b) Common Fisheries Policy, and Common Market Organization in Fishery and Aquaculture Products (EU, 2013a) are examples of such endeavors.

Addressing market power concentration and *business structure* could play a crucial role in enabling fair profit distribution and maintaining economically viable food supply chains (Bock et al., 2022; EU, 2019b). A balanced market strengthens the EU's competitiveness in the food system and creates new opportunities for businesses, as highlighted in the F2F Strategy (EC, 2020c), the Common Agricultural Policy (EU, 2021c), and the Common Fisheries Policy and specifically in its first component, the Common Market Organisation in Fishery and Aquaculture products (EU, 2013a). This is also recognized in Hebinck et al. (2021), which points to the significance of balancing bargaining power within the food supply chain to prevent unfair trading practices. The current indicators such as producers' investments, producer organizations (e.g., the share of production marketed by producer organizations), and market concentration are a good representation of the power that producers hold in the food system.

Monitoring *income distribution* within food systems is essential, as emphasised in the F2F Strategy (EC, 2020c), CAP (EU, 2021c) and Bock et al. (2022). These sources highlight the importance of sustainable livelihoods, fair income distribution and profitability for primary producers, while also recognising the insecurity and inadequacy in livelihoods related to food systems as noted by Fanzo et al. (2021). In this domain, there are sufficient data to cover terrestrial food production systems, as both the comparison of farmers' incomes with the rest of the economy, as well as the average salary along the food chain are available. However, for fisheries and aquaculture systems, data remain to be incomplete.

Low-price volatility is vital for guaranteeing stability and price affordability and thus, for food security in the EU (EU, 2021c). Consequently, monitoring food, primary producers' input, and commodity prices is essential for assessing the stability and economic sustainability (Béné et al., 2019; EC, 2020c; Hebinck et al., 2021; Bock et al., 2022; Schneider et al., 2023). Adequate data are generally not a concern for indicator generation, as they are accessible for a variety of agricultural and fisheries outputs and inputs, although data may be lacking in some areas (such as aquaculture first sale data, where no legal reporting obligation exists).

Monitoring *trade* is fundamental for assessing competitiveness in global markets, particularly given the EU's significant role in international trade on food products, and for evaluating the impact on local food security and sustainability (Hebinck et al., 2021; Bock et al., 2022).

3.2.7 Development and logistics

Regarding *technology and digitalisation*, various EU initiatives highlight the importance of training, research and innovation, emphasising the need for fast and reliable internet access for all rural areas EU Digital Strategy 2024,[4] F2F Strategy (EC, 2020c), Bioeconomy Strategy (EC, 2018a). Investments in food systems research and development are also seen as critical for building strong and resilient food value chains (Hebinck et al., 2021) and a fair business environment (Bock et al., 2022). In addition, emerging technologies and innovation can play a significant role in the transformation of food systems (Herrero et al., 2020).

Transportation and logistics are also key elements in the food supply chain. Bock et al. (2022) highlight their significance for enhancing sustainability within the food value chain. The F2F Strategy (EC, 2020c) points to the importance of reducing reliance on long-haul food transportation. Promoting shorter supply chains can strengthen regional and local food systems. Similarly, the Bioeconomy Strategy (EC, 2018a) mentions that multi-product biorefineries should ideally be located close to primary production sites to prevent high transportation costs and boost local economies.

3.2.8 A fair, inclusive and ethical food system

Supporting the viability of livelihoods and fair, decent working conditions for all involved in the food system is an important goal outlined in the reviewed food system frameworks (Supplementary Table S2). The proposed monitoring domains on *employment and working conditions* and on *social protection and poverty* focus on factors influencing the lives of millions working in the EU food system and that align with EU's social welfare objectives under the European Pillar of Social Rights (EPSR) (EC, 2020b). The EPSR is a guiding principle for a more inclusive society, covers social protection and working conditions, and is integral to transitioning toward a sustainable food system (EC, 2020c).

Social protection is also central to reduce inequalities and ensure access to healthy and nutritious food for the most vulnerable (HLPE,

4 https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/europe-fit-digital-age/europes-digital-decade-digital-targets-2030_en

2012; Fanzo et al., 2021). Empowering women in the food system and supporting and attracting young generations further contribute to sustainability (EC, 2020c, 2020e). Finally, promoting *animal welfare* in the EU (EU, 1998; EC, 2020c) manifests that the health and well-being of animals, people, plants and the environment are deeply interconnected (FAO et al., 2022).

3.2.9 Food environment

The creation of favorable food environments that make sustainable food choices easier for consumers is a key element for transforming food systems and relevant for tracking progress (EC, 2020c; Fanzo et al., 2020; SAM, 2023). Consumers are not always in control of their food choices and the physical, economic and social context in which they make food choices plays a central role in creating opportunities for more sustainable behaviors (SAM, 2023; HLPE, 2017). Factors such as food availability, price of food, the information environment, social norms and individual daily routines are all important aspects of food environments (SAM, 2023). The complex task of addressing food environments is a reflex of understanding people's realities (Hawkes et al., 2024). Recognizing these limitations, we adopted the proposal by Fanzo et al. (2020) which builds on the High Level Panel of Experts on Food Security and Nutrition concept of food environments (HLPE, 2017) and integrate food availability, food affordability, properties of food (including food composition, convenience or sustainability value) and food messaging as domains in our framework. These aspects have also been highlighted as central for enabling supportive environments toward sustainable food consumption in the EU (SAM, 2023).

Currently, the FAO globally collects indicators to monitor *food availability* and *affordability*.[5] However, to track progress in these domains, monitoring physical food environments (such as public procurement and public meals), or observing affordability of healthy diets in the EU would add great value. *Properties of food* can include attributes such as food safety, flavor, convenience, but also food composition and its nutritional and sustainability value. For instance, reformulating food products to reduce fat, salt or sugar and the introduction of healthier, plant-based alternatives can enable the access toward healthier and more sustainable food products (SAPEA, 2023).

Challenges also persist in monitoring *food messaging*, but recent EU Joint Action programs show opportunities for improvement in the areas of marketing (monitoring advertisement of unhealthy foods targeted at children) and monitoring the nutritional quality of food offer (Dias et al., 2023; Muc and Tatlow-Golden, 2023). In the absence of detailed indicators, the Healthy Food Environment Policy Index could have the potential to monitor the quality of policies (Pineda et al., 2022) that influence the food environment. However, this indicator is currently limited to a few EU countries and relies on national expert-judgments. Overall, the availability of adequate indicators in the food environment domains is limited which compromises our capacity in monitoring progress toward healthier and sustainable food environments.

3.2.10 Nutrition and health

Diet change is central to the food system transformation (Vermeulen et al., 2020). The *Nutrition and healthy, sustainable diet* domain focuses on tracking the dietary transition toward healthy, sustainable diets. Possible dietary aspects for monitoring can be identified by reviewing the related definitions, principles and recommendations (Afshin et al., 2019; EAT, 2019; FAO and WHO, 2019). From a dietary perspective, healthy and sustainable diets are predominantly abundant in fruit, vegetables and include legumes, whole grain, nuts and moderate amounts of animal-sourced foods and small amounts of red meat. Free sugar, salt, saturated fatty acids and alcohol are equally important nutritional aspects linked to the healthiness of diets (FAO and WHO, 2019). However, monitoring diets remains challenging as regularly updated estimates from national dietary surveys are often limited and countries use different methods to collect food consumption data (European Food Safety Authority, 2014).

Different global initiatives have tried to overcome the absence of updated food consumption data by providing modeled estimates but differences in the estimates indicate poor reliability for monitoring and comparison across countries (Beal et al., 2021). In the EU, however, the EFSA's EU Menu project aims to support harmonization of food consumption data. The EFSA's Comprehensive European Food Consumption Database offers valuable information on food consumption, serving as a possible basis for developing adequate indicators.[6]

Linked to poor and unhealthy diets, the *health impact from diets domain* aims to monitor the public health progress in the EU. Currently, high prevalence of excess weight and obesity in the region is a major risk for many non-communicable diseases including diabetes, cardiovascular disease and certain types of cancer (EC, 2020c), which threatens the quality of life of individuals and the sustainability of healthcare systems, affecting social national budget spending. The WHO's European Childhood Obesity Surveillance Initiative (COSI) monitors prevalence of childhood obesity in many European countries (WHO, 2022). The Global Burden of Disease (Afshin et al., 2019) tracks the burden of disease attributable to dietary risk factors quantifying its health impact.

Achieving food security is connected to countries' efforts in ensuring the right to adequate food for all. In the EU, many policies (under the EPSR action plan or the CAP) contribute to the implementation of the right to food by increasing social protection, supporting and reducing inequalities in the access to healthy food to achieve food security. Still, billions of people lack access to adequate, nutritious, and safe food that satisfies dietary needs and food preferences globally (FAO et al., 2023). Food insecurity has detrimental impacts on human health and well-being, and it is strictly related to the quality of food environments, which influence access to healthy diets. Food insecurity at moderate levels of severity is typically associated with the inability to regularly eat healthy and balanced diets. High prevalence of food insecurity and the associated unbalanced diets can be considered as predictors of various forms of diet-related health conditions, also manifested by micronutrient deficiency. Recent geopolitical and food crises have revealed the fragility of food systems, leading the EU to act in the support of regional and global food security to protect consumers and farmers (EC, 2023i).

5 https://www.fao.org/faostat/en/#data

6 https://data.europa.eu/data/datasets/the-efsa-comprehensive-european-food-consumption-database?locale=en

3.2.11 Governance

Governance is the 'process by which societies negotiate, implement, and evaluate collective priorities while building shared understanding of synergies and trade-offs among diverse sectors, jurisdictions, and stakeholders' (UN, 2021a). Governance also relates to guiding visions, principles and values that influence the interaction among institutions, civil society and consumers toward sustainable food systems (Fanzo et al., 2021). In terms of outcomes, the governance of food systems can be defined as the capacities to integrate conflicting interests in a coherent policy, providing the necessary institutional and financial background for its implementation. In our framework, we acknowledge the proposal of Fanzo et al. (2021), which includes *strategic planning, effective policy implementation, participatory processes* and *accountability* as key elements for monitoring food systems governance.

Policy makers need to approach the food system as a complex and dynamic system increasing their capacity to deal with the systemic impact of decisions and actions (Leip et al., 2023). Governing the food systems transformation thus requires more inclusive and systemic approaches, promoting multi-level governance and establishing good coherence, reflectiveness and articulation (Kugelberg et al., 2021). As such, governments need to increase their capacity for governing a food system transition by exploring a combination of policy measures that promote more inclusive and systemic actions (Leip et al., 2023).

In the EU, increasing the coherency and articulation of food system policies is an opportunity to support Member States in the development of actions aligned with shared goals for the region (Fesenfeld et al., 2023). However, according to the subsidiarity principle, the main responsibility of implementing such policies remains at national, regional or local levels. This is increasingly valid even for the Common Agricultural Policy, the most centralized EU Policy, where the latest regulation empowers Member States to define their own strategic plans. In the Common Fisheries Policy the management is shared between national competent authorities (fishing quotas) and the operators of the sector (Common Market Organization).

The implementation of national food system strategies based on good principles of governance can steer and accelerate food systems transformation (Kugelberg et al., 2021). Budgetary disbursements may indicate the stability and level of commitments to sustainability objectives of the governments (Fanzo et al., 2021). For instance, the integration of sustainability in the development of food based dietary guidelines is an opportunity to inform and guide the implementation of national food policies recognising the systemic impact of food choices (Costa Leite et al., 2020; SAPEA, 2023).

3.2.12 Resilience

Resilience is the system's capacity to adapt and respond differently across its diverse components (Seekell et al., 2017; Zurek et al., 2022). It is identified as a horizontal thematic area, as it represents a cross-cutting property within the food system. It includes inter- and transdisciplinary perspectives on emerging socio-economic, environmental and governance challenges. This overarching concept characterizes the capability of the food system, from primary production to food and nutrition security, to withstand and recover from shocks while maintaining its core structure, and adaptability during changes and pressures (Manca et al., 2017; Guyomard et al., 2020).

There is no universal agreement on whether resilience truly constitutes a dimension of (food system) sustainability (Béné et al., 2019). However, many other food system frameworks include resilience as an important aspect to consider for food system sustainability (Gustafson et al., 2016; Fanzo et al., 2021; Bock et al., 2022).

While there are global frameworks assessing food system resilience (Constas et al., 2021; CBD, 2023), they often rely on a set of indicators that do not fully capture the unique aspects of resilience within the European context. Despite commendable efforts to quantify resilience at the country level, these approaches tend to emphasize broad metrics, such as economic impacts of disasters and infrastructure availability, which do not sufficiently address the EU's specific regulatory, social, and environmental standards. This limitation highlights the insufficiency of a limited set of variables focusing on specific aspects of resilience for a comprehensive assessment within the EU context. Consequently, there is a need for developing a tailored methodology that more accurately reflects the complexities and unique characteristics of the EU's food system resilience.

To assess food system resilience, we have designed a framework that holistically integrates the key aspects of resilience (Davis et al., 2021; Zurek et al., 2022) - *preparedness, shock resistance, adaptation, and transformation*. Preparedness focuses on strategic planning for unforeseen events. Shock resistance entails the system's ability to absorb sudden disruptions; adaptation refers to adjusting to changing conditions; transformation relies on making fundamental changes to respond to long-term shifts. The EU Contingency Plan (EC, 2021a) further supports this by establishing proactive measures for preparedness and rapid recovery mechanisms, ensuring the stability and security of the food system during crises and facilitating a transformative shift toward sustainability in response to long-term challenges.

Each aspect of resilience is characterized by resilience capacities and vulnerabilities (Tendall et al., 2015; Seekell et al., 2017). They characterize the opposing factors that influence the food system's ability to cope with, adapt to, and recover from stressors and shocks. Integrating resilience thinking into policy, and into practice, will result in a robust food system that enhances societal well-being and ensures the prosperity of future generations, without overlooking the potential trade-offs between resilience and sustainability.

3.3 Potential indicators for the monitoring framework

From the initial collection of 247 indicators, we excluded those that did not fit the purpose in terms of their relevance or were duplicates (i.e. the same indicator used with different names). Supplementary Table S5 presents the pool of the resulting 180 indicators. Every indicator, classified according to the supply chain components, sustainability dimension, thematic area and domain, is presented, together with the data sources. It should be noted that this pool also contains indicators with missing data points, incomplete geographic coverage, or insufficient data quality. In some cases, an

 10.3389/fsufs.2024.1502081

indicator is relevant to multiple domains, i.e., can be considered as multi-purpose, according to Eurostat definition for the EU SDG indicators. To facilitate the discussion of indicators, in such cases, we assigned a primary domain. The choice of primary domain builds on the highest relevance agreed by the respective thematic experts.

From the total of 180 indicators, 54% belong to the environmental, 29% to social, and 17% to economic dimensions. Taken together, they cover all parts of the supply chain. Considering that an indicator can relate to more than one element of the food supply chain, most of them cover primary food production (77%), 40% focuses on food consumption, almost quarter on food processing (23%) and food distribution (23%). Besides the 16 consumption footprint indicators, only 12 indicators include all the supply chain components (such as greenhouse gas emissions, food loss and waste, or consumer food inflation).

It is important to note that many of the 180 indicators collected within this framework are also linked to other EU policies (currently 22 listed in Supplementary Figure S2). This reveals how different policy areas are interconnected and the potential of the EU food system monitoring framework to integrate elements from other policies.

3.4 Indicator gaps

Having defined the initial list of domains with general or specific knowledge gaps the thematic experts identified possible directions of further research to develop indicators that contribute to the completeness of the monitoring framework. In this section, we summarize the main knowledge gaps related to food system sustainability, which is manifested either in absence of suitable data, or in lack of sound methodology for calculating the indicators. An overview table of knowledge gaps is given in Supplementary Table S6.

3.4.1 Environmental dimension

While there are indicators available for measuring overall GHG emissions from the food sector in the EU (Crippa et al., 2021) and the related consumption footprints (Sala et al., 2023), the climate change thematic area lacks emission data per product type (e.g. crop types, livestock species, and processed food with different origins of production). Emissions associated to different management practices (like tillage) are also missing, despite their importance is highlighted by the IPCC (2019). In the pollution domain, a major challenge in evaluating the impact of agricultural inputs is the absence of spatially detailed and temporal data that includes the actual quantity of active substances. This does not allow to use comprehensive environmental risk assessment indicators, such as the pesticide load indicator (Möhring et al., 2020). With current developments in LCA, the food Consumption Footprint indicators could incorporate the impacts from plastic litter in further developments.

In the domain of antimicrobial resistance, the main difficulty relates to understanding the proliferation and dissemination of antimicrobial-resistant bacteria originating from livestock organic waste (Goulas et al., 2020) and their impact on the environment, human and animal health. This jeopardises the development of standardized indicators for antimicrobial resistance surveillance in water bodies (Andrade et al., 2020) and crops (Larsson et al., 2018). While there are reliable data on the sales of antimicrobials for use in food-producing animals in the EU (EMA, 2023, 2024), the extent of use of antimicrobials in other sectors of the food production remains unclear. Council Recommendation (CEU, 2023) called for integrated systems for the surveillance of antimicrobial use and resistance, encompassing human, animal and plant health, food, wastewater and the environment (water and soil) to combat antimicrobial resistance (AMR).

Gaps are also persisting in the Sustainable use of resources thematic area. Concerning the water domain, while water security for irrigation in agriculture is an important factor of resilience, the knowledge on the use of more sustainable practices, such as reusing reclaimed (grey) water is scarce. The situation is similar, when it comes to water usage for each supply chain component beyond the primary sector.

Data for measuring the competition of different agricultural land uses (i.e., area of land dedicated to food, feed and biofuels) are also incomplete. Even though crop statistics provide a proxy, the share of different uses could be further refined by commercial data or more detailed data on crop varieties.

Despite recent efforts, information on the water-based food systems is still incomplete and an overall assessment of sustainable aquaculture practices, to measure their environmental, social and economic impacts is difficult. In terms of energy use in the food supply chain, the information on food distribution and food consumption is still blank.

While the wildlife population survey provides robust information on the main drivers of biodiversity loss, monitoring certain dimensions of biodiversity remains incomplete. For example, understanding the impact of invasive alien species on agro-ecosystems and on the aquatic environment and their distribution due to agricultural or other activities remains challenging. The area covered by bottom-contact fishing gears and from data on bycatch is insufficient. Measuring ecosystem services of aquaculture is another area to explore (e.g., cost estimates of lost benefits from a degraded aquatic ecosystem). In terms of genetic biodiversity, data on the in-situ crop and breed diversity are scarce.

Concerning the overall circularity in the EU food sector, the current indicators like material footprint and circular material use rate (EC, 2023c), if applied to the EU food system, could provide a macro-scale view. However, academia calls for indicators that focus on the broad spectrum of the circular economy. For example, the use of manure as an organic fertilizer (Köninger et al., 2021) and an updated nutrient balance are important indicators for the (re)use of nutrients in soil fertility (Moraga et al., 2019). Quantifying the use of by-products of food processing for feed, energy generation, or production of biobased materials would inform on the amplitude of good practices and could be used for promoting the sustainability of the food system. Similarly, using food loss and waste for energy generation is another unexplored area.

3.4.2 Economic dimension

The existing data in the economic thematic area focus on the production and manufacturing sectors. To extend the range of indicators, more information is needed on food distribution and consumption. This data gap is particularly evident in the Sectorial Growth domain, where there is a lack of information on the distribution and food service sectors.

Addressing market concentration in the entire food value chain is challenging, as data are limited in certain stages, for example, in food service. While it would be ideal to include an indicator for the value of production under EU quality schemes per product group, a proxy with the number of products under these schemes is currently accessible. Despite the availability of various data to measure trade (e.g., trade balance, import dependency), assessing the fair trade (such as fair income, quality, valorization and added value of food products) remains challenging.

Data on technological advances such as precision farming or emerging digital techniques and innovation in novel food products (e.g., insects, algae, alternative animal protein production, and precise fermentation) are underrepresented, despite they may play a key role in improving the sustainability of food systems. In terms of logistics, data gaps are linked to emerging distribution channels such as online retailers and home food delivery and to more sustainable forms of transportation (e.g., electric vehicles, railway).

3.4.3 Social dimension

While existing data (from Eurostat and the International Labor Organization) can be explored to monitor employment, working conditions, social protection and poverty across EU countries, there is a lack of specific indicators related to employees working in the food system. Furthermore, there are special aspects, like unreported and unsalaried work that are especially relevant in small-scale farming and fisheries. More detailed variables on salaries categorized by job type, age, and gender would provide better insight into the social sustainability of the sector. A particular aspect is shadow economy and illegal employment that are frequently linked, but not limited, to seasonal work. Individuals engaging in shadow economic activities actively avoid detection (Schneider and Asllani, 2022) and due to this elusive nature of the illegal employment of workers, statistics are scarce, unreliable and hard to compare across countries (OECD, 2018).

To properly account for the global social impact of EU trade, the extension of the footprint methodology is proposed (Mancini et al., 2023), to provide such values by product groups. However, further adaptation is needed to account data related to the different member states of the EU.

Data on animal welfare are also scarce. To assess the progress toward welfare friendly livestock production systems, harmonized and comparable data, such as on cage-free farming methods, stocking densities, mutilations and duration of transportation would be needed. In the absence of such data, proxies on the share of products adopting animal welfare practices above EU legislation on animal welfare (e.g., organic animal farming) could be used (Hebinck et al., 2021). Food labels often communicate attributes linked to animal welfare practices including on activities linked to transport, housing, animal health and feed (EC, 2023k).

To monitor the progress toward healthier and sustainable food environments efforts are needed to increase data quality and availability across many domains. In the context of EU Joint Actions, progress has been achieved in the areas of food marketing and food reformulation indicating promising pathways toward the development of potential indicators (Dias et al., 2023; Muc and Tatlow-Golden, 2023).

To deal with the health impacts of diets, food consumption estimates from national dietary surveys are desired. Indicators concerning green public procurement and the provision of healthy and sustainable meals in schools and public institutions could inform on the progress within the context of such physical food environments.

As a priority issue for the EU, the development of indicators to better monitor the access to healthy diets would be required (Herforth et al., 2020). To advance the monitoring of affordability of healthy, sustainable diets more dialogues and consensus on the methodology would be valuable.

3.4.4 Horizontal thematic areas

Understanding how food system policies are designed and implemented is essential to evaluating their effectiveness in delivering coherent and coordinated actions across different domains, scales and time.

While some initiatives have assessed the quality of policies shaping food environments, there is limited data on comprehensive, systemic government approaches to national food systems (Pineda et al., 2022). Nevertheless, existence of legal acts on food law and sustainability may provide a starting point to understand the related implementation efforts. Defining simple and meaningful metrics for Participatory processes and Accountability are more challenging, even though they are crucial to achieve a well-functioning food system governance.

Currently, there is no clear consensus on how to measure resilience, as this is typically considered to be an abstract concept (Jones, 2019). The Resilience dashboards[7] provided in the context of the 2020 strategic foresight report and its updates establish a selection of indicators relevant to assessing resilience but do not provide aggregated metrics for the identified dimensions, their areas or classes. Therefore, as indicated in section 3.4, the main knowledge gap is related to the methodology, including the selection of variables to consider, their weights and the aggregation method to develop a few, but meaningful indices.

4 Discussion

4.1 EU food system monitoring framework

Effective monitoring of the EU's transition to sustainable food systems can increase policy coherence and provide better evidence for informed policy making. In the EU, several policies impacting the food system are already monitored (EC, 2023b, 2023f, 2023j; EEA, 2023b; Gras et al., 2023). We also considered global frameworks aiming to monitor the food system transformation (Fanzo et al., 2021; Schneider et al., 2023). This paper tailors a framework to the needs of the EU, building on its existing initiatives and focusing on specific aspects in the EU region. The selection of thematic areas, domains, and indicators was guided by their significance in the EU food system and their consistency with EU policy priorities. This involved integrating additional domains, such as the circular economy and the consumption footprint. We also included governance and resilience as horizontal thematic areas in line with other monitoring initiatives (Fanzo et al., 2021).

7 https://commission.europa.eu/strategy-and-policy/strategic-foresight/2020-strategic-foresight-report/resilience-dashboards_en

Applying the DPSIR framework supported the selection and categorization of indicators by identifying causal relationships between the elements. For example, governance and resilience indicators are more linked to drivers and responses, distinguishing them from the thematic ones that deal with pressures, impacts and states within the three sustainability dimensions.

To select the indicators, we adopted a dual perspective, examining them from the point of view of sustainability (defined in the thematic areas and domains) and the components of the food supply chain. This approach acknowledges that food system sustainability goes beyond primary production and food consumption. It also reveals that new data sources and methods are necessary to assess the middle components of the supply chain. Moreover, to estimate the global impact of EU food systems, we proposed to include indicators such as the consumption footprints. Accounting for the 'non-food' components of agricultural production (such as feed and biofuels) opens an additional, but very relevant aspect, where trade-offs between different uses of land and policy goals must be achieved.

In the present study, we identified a set of potential indicators to monitor the EU food system. However, we also found significant data gaps. They are related either to the lack of data collection, or to insufficient quality (e.g. weak methodology, patchy time and geographical coverage) of existing indicators. In particular, the lack of metrics to monitor the progress toward a more ethical food system, healthier food environments and healthy and sustainable diets, as well as the lack of systemic indicators covering the whole supply chain were identified. The revealed gaps will help in conceptualising new indicators and enhancing data completeness to underpin an improved monitoring framework.

We note that the gaps listed in Supplementary Table S6 reflect the insights of experts involved in developing the food system model and screening the indicators. Consequently, this list may not cover all aspects comprehensively, as a thorough scientific literature review has not taken place. Further engagement with stakeholders and emerging policy initiatives are likely to uncover additional areas that require research.

The monitoring framework should also be flexible to cope with the dynamics of the food system and the evolving nature of the related policies, while serving its original purpose. The indicators collected for this framework need to be periodically revised to add new, or replace the obsolete ones due to emerging data collection or research. The interlinkages between the elements can help assessing complex trade-offs across climate, environment, economic and social viability. As monitoring food systems integrates data from many different sources, it requires agile knowledge management tools. Beyond finding relevant data and indicators, one of the biggest challenges is associated to their reusability. Publicly accessible repositories (registries) that contain data validated and maintained by competent controlling bodies would greatly support interoperability.

We are aware that the 'reusing existing' principle may raise questions concerning the validity of the proposed indicators in the context of the EU food system. However, the quality evaluation process scrutinized the relevance of each indicator linking them to specific requirements of different European initiatives. This approach helps avoiding duplication of efforts including the administrative burdens of the Member States (EC, 2022b).

Despite the presented monitoring framework is the result of a multidisciplinary team of experts, extending dialogues to a wider range of stakeholders can be central to support the validity of our work while ensuring a more inclusive approach. It can contribute to addressing knowledge gaps improving its completeness and enhancing its general acceptance. For example, employing Delphi method could deliver complementary perspectives, fostering consensus-based and innovative metrics tailored to emerging priorities. In our specific case, reusing existing indicators is instrumental for coherence with other EU initiatives, such as the 8th Environment Action Plan monitoring framework (EC, 2022b), the Performance Monitoring and Evaluation Framework of the CAP (EC, 2023b), or the Resilience dashboards.

To implement our framework, as stated in section 2.3, we used DataM. In our view, such an integrative platform that uses common semantics and interoperable data is indispensable to guide participatory processes and foster collaboration among the scientific communities, policymakers, and stakeholders in a transparent and cost-effective way.

4.2 Policy implications

The production, processing, distribution and consumption of food, as well as the related environmental, economic and social impacts fall under a wide range of EU policy areas and instruments. The need for introducing a system to monitor the sustainability of the EU food system was raised for the first time in the European Green Deal (EC, 2022) and the F2F Strategy (EC, 2020c) underlining the ability to deal with the complexity and trade-offs of the food system. Consequently, the implementation of a food system monitoring framework aims to augment policymakers' access to comprehensive information and advocates for an overarching system-oriented approach that recognises the interdependencies between all food system components and sustainability aspects. At the same time, it also provides a basis to identify gaps where further actions are needed.

A fit for purpose monitoring framework in the EU requires agreed priority areas recognized by all stakeholders involved in the food system transition. This includes, where possible, the development of distance to target indicator, that track progress toward the agreed goals and provide a better understanding of the food system performance toward sustainability (Fanzo et al., 2021; Hebinck et al., 2021). Since evidence-based policy-making requires data, the identified data gaps signal collaboration need at national and regional levels with the engagement of public and private institutions.

The proposed food system monitoring framework may be relevant for many policy areas within the EU and its member states. Since various policies impact and/or are impacted directly and indirectly by the food system, its monitoring requires a comprehensive representation of diverse policy areas, aiming to promote coherent analysis and subsequent actions through its array of indicators. Many indicators (Supplementary Figure S2) within this framework are used for monitoring several EU policy initiatives within and beyond food systems. This coherence facilitates a holistic understanding of the interrelations between policies and the food system, fostering aligned actions across multifaceted policy landscapes.

The developed monitoring framework also can act as a bridge between the sustainable transformation of the EU food system and the achievement of the SDGs by offering actionable indicators that systematically track progress. This alignment links the EU's sustainability objectives to global targets, fostering policy coherence with global aspirations. Its structured approach promotes consistency across policies and stakeholder actions, guiding the EU food system's transformation while supporting the broader goals of the 2030 Agenda for Sustainable Development.

The knowledge and insights gained from the monitoring system outlined in this article could be made available to various entities, including EU member states authorities, regional and local government bodies, as well as other public and private stakeholders. To improve its usability, further consolidation and selection are necessary, based on consultation with EU and national policy makers and the stakeholders concerned.

When implemented, the EU food system monitoring framework can play a critical role in all stages of the policy cycle, including agenda-setting, policy formulation, decision-making, implementation, and evaluation (Hebinck et al., 2021). It can support evidence-based processes by informing and guiding stakeholders through areas of sustainability relevance. Additionally, the framework facilitates multi-stakeholder dialogues and negotiations, particularly in setting targets, decision-making, and monitoring policies and trade-offs, enabling more inclusive and comprehensive approaches to addressing sustainability challenges.

5 Conclusion

Adequate monitoring of the EU transition toward sustainable food systems can enhance policy coherence and provide better evidence for informed policy making. We propose an initial concept and methodology for a future EU food system monitoring framework, integrating evidence from the scientific literature tailored to the EU context.

The framework integrates insights from previous EU participatory processes and results from extensive dialogues among experts with interdisciplinary backgrounds. In order to make progress and operationalize it, as a next step, focused participatory and consultative processes are essential, both with wide range of policy makers and stakeholders to ensure inclusive and transparent dialogues.

The indicators screened during the development of the monitoring framework are a good basis to start providing data for better informed decision-making, facilitating the identification of synergies and trade-offs. This underscores the value of a holistic approach, which addresses various thematic areas under the food system umbrella considering the entire supply chain and a wide range of sustainability aspects. It also highlights areas where available data for monitoring and tracking progress are currently limited.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found at: the data sources, linked to the specific indicators, are indicated in Table SM5 of the Supplementary material, and the references of the manuscript. All data come from public and open sources and are referenced as they appear in the text. The implementation of the EU Food System Monitoring dashboard has begun, and selected indicators are now available at: https://datam.jrc.ec.europa.eu/datam/mashup/EU_FOOD_SYSTEM_MONITORING/.

Author contributions

SA: Data curation, Visualization, Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing. JC: Writing – original draft, Writing – review & editing, Conceptualization, Data curation, Investigation, Methodology. ES-M: Writing – original draft, Writing – review & editing, Conceptualization, Data curation, Investigation, Methodology, Visualization. AC: Data curation, Methodology, Writing – original draft, Visualization. RC: Data curation, Investigation, Methodology, Writing – original draft. J-ND: Data curation, Investigation, Methodology, Writing – original draft. FM: Data curation, Investigation, Writing – original draft. BJ: Data curation, Investigation, Writing – original draft. IG: Data curation, Investigation, Writing – original draft. PG: Data curation, Investigation, Writing – original draft. RM'b: Data curation, Funding acquisition, Writing – original draft. PP: Data curation, Investigation, Writing – original draft. CP-P: Data curation, Investigation, Writing – original draft, Writing – review & editing. ST: Data curation, Software, Visualization, Writing – original draft. JW: Data curation, Investigation, Writing – original draft. KT: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2024.1502081/full#supplementary-material

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