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DOI:
10.3389/frsus.2023.1231684

frontiers | Frontiers in Sustainability

TYPE Original Research
PUBLISHED 30 October 2023
DOI 10.3389/frsus.2023.1231684

OPEN ACCESS

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RECEIVED 30 May 2023
ACCEPTED 06 October 2023
PUBLISHED 30 October 2023

CITATION
Moreira-Dantas IR, Martínez-Zarzoso I, de Araujo MLF, Evans J, Foster A, Wang X, Thakur M, Jafarzadeh S and Martin MP (2023) Multi-stakeholder initiatives and decarbonization in the European food supply chain. *Front. Sustain.* 4:1231684. doi: 10.3389/frsus.2023.1231684

Multi-stakeholder initiatives and decarbonization in the European food supply chain

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The European Green Deal is a political milestone aiming to promote a carbon-neutral economy in the European Union. Decarbonizing the complex food sector requires the unified interaction among effective climate policies, economic instruments, and initiatives involving multiple stakeholders. Despite increasing efforts to highlight the importance of innovations and finance to achieve sustainable food supply chains (FSC), comprehensive information about related opportunities and barriers to mitigating emissions in the food sector is still under-explored. To cover this gap, this paper applies an existing industrial policy framework under the lens of the EU FSC to identify potential strategies that should help achieve the needed financial means and innovation actions, as well as to gauge political alignment across FSC stages. Methodologically, the pillars proposed in the framework are linked to multi-stakeholders' initiatives engaged in achieving net-zero emissions. The paper highlights three main implications of the identified interlinkages. First, political directionality related to the food sector should be more comprehensively tailored to account for the specificities of all stages of the FSC. Second, research and development projects shall likewise cover all stages, instead of emphasizing only food production and agricultural systems. Finally, multiple stakeholders are crucial as promoters of technology and innovation towards a green economy. Nevertheless, initiatives should be integrated into political discussions in order to promote civil awareness, sustainable food and services demand, aligned to political guidelines.

KEYWORDS

food supply chain, European green deal, farm to fork strategy, sustainable food systems, decarbonisation

1. Introduction

The European Green Deal (EGD) heralds a new era for European Union policies, in which industries shall decarbonize their operations by 2050 (European Commission, 2019). To promote a carbon-neutral economy, the European Commission (EC) has announced a number of policy measures, subsidies, and financial resources for continuous investments in sustainable ventures and clean technology (European Commission, 2023a). The food sector is a central component of this transformation, not only due to its significance in poverty alleviation and food security, but also because greenhouse gases (GHGs) are emitted throughout all stages of the food supply chain (FSC) (Garnett, 2011). Moreover, environmental degradation and biodiversity loss are also a result of unsustainable farming practices (Zingale et al., 2022). Given the mounting demands for food and energy, ensuring sustainable operations from farm to fork can only be achieved with massive structural changes, while acknowledging that the food sector is a key GHG emitter and simultaneously very vulnerable to climate change (Myers et al., 2017; Del Borghi et al., 2022).

The FSC is a complex system encompassing activities that produce, add value and supply food products and services to final consumers (Moreira-Dantas et al., 2022a). The EU FSC is highly integrated with numerous small and medium sized enterprises (SMEs) as well as a limited number of multinational companies that have production facilities acting locally, regionally, nationally and internationally (Kühne et al., 2010). As shown in Figure A1 in the Appendix the food and beverage industry accounts for 16% of the total manufacturing sector in the EU, compared with rubber and plastic (7%), wood and paper (5%), and textiles (3%). This indicates the food sector's relevance in terms of jobs and value added. Moreover, food exports have shown a growing path over time, contributing to a positive trade balance (European Commission, 2023b). In terms of sector internationalization, the European food sector has experienced steady growth both in value and in share of total exports. Figure A2 in the Appendix indicates that the EU food and beverage exports grew in value by around 80% between 2010 and 2021, with the food sector's share expanding over the considered period. These growth trends have important environmental implications. According to EDGAR[1] estimations, about a third of global anthropogenic GHG emissions originate from the food sector. Crippa et al. (2021) found that such emissions are mainly driven by energy use, industrial operations and waste management. Moreover, it is argued that even if fossil fuel emissions from these sources were reduced, the Paris Agreement target of staying below 1.5°C would not be achieved if the food sector's emission patterns follow their current trend (Clark et al., 2020).

While food production, land use and land use-change stages have been the focus of several political strategies to promote sustainability standards, achieving carbon neutrality will only be possible with more efforts to reshape industrial operations within and beyond the farm gate. Such efforts lie in decarbonizing current industrial activities while continuously incorporating new net-zero technologies (Bataille, 2020). Moreover, political enforcement, investments, and initiatives by both industries and citizens should align with regional priorities, capacities, and conditions (Bataille, 2020). In fact, coupling various regulatory, financial, industrial, and civil contributions might be an optimal way to enable an effective and prompt transition to a net-zero and equitable food sector, as proposed by the farm to fork (F2F) strategy (Schebesta and Candel, 2020). In this context, achieving the F2F premises is a costly exercise, requiring the reallocation of resources along the entire FSC (Wesseler, 2022). Indeed, past technological improvements in the food industry are not able to offset the current and future costs envisioned by the F2F strategy (Barreiro-Hurle et al., 2021).

By comparing European *per capita* GHG emissions along the FSC in two distinct periods (2001–2009 and 2010–2018), Moreira-Dantas et al. (2022a) argue that EU countries have shown overall progress in decarbonizing FSC stages. Countries reduced emissions at different stages, but emissions coming from post-farm gate activities (e.g., processing, retail, transport and logistics) remained relatively unchanged. Moreover, fluorinated gas (F-gas) emissions coming from food retailing have increased over time. This fact calls for a reshaped working plan to decarbonize the FSC in the framework of a multi-stakeholder engagement. So far, a clear design of applicable strategies to decarbonize food industrial activities seem to be absent, partly due to the lack of standardized corporate GHG reporting (Busch et al., 2022). Furthermore, available reports for scope 1 and scope 3 emissions in the food-related industries are limited and incomplete (Hansen et al., 2022). Likewise, comprehensive and systematic information about opportunities and barriers to mitigate emissions in the food sector is still lacking, despite increasing efforts underpinning the roles of innovation and finance in promoting sustainable FSC.

This paper aims to address this gap in the literature by applying the industrial policy framework proposed by Nilsson et al. (2021) under the lens of the EU FSC. Using a systematic collection of the initiatives of multiple stakeholders (Moreira-Dantas et al., 2022a,b), we identify the extent to which these actions align with the sustainability and decarbonization goals of the European food sector. Thus, by linking the industrial policy framework to the identified policy and stakeholders' actions, we are able to provide potential ways to transform food industries following specific criteria and comprehensive instruments.

The paper is structured as follows: Section 2 details the industrial policy framework as well as the search for initiatives. Section 3 presents the results and a critical discussion of the findings, followed by conclusions in Section 4.

2. Methods

The main methodology consists of establishing links between Nilsson et al. (2021) industrial policy framework and the systematic collected range of initiatives from multi-stakeholders that aim at decarbonizing the FSC (Moreira-Dantas et al., 2022a,b). We start by presenting the six pillars of the industrial policy framework, then move to briefly describe the groups of stakeholder initiatives and finally the interlinks are shown.

The six integrated pillars of the industrial policy framework (Nilsson et al., 2021) inform about key areas of improvement and political gaps within the context of the FSC. First, *Directionality* refers to the guidelines and objectives proposed by governmental bodies to achieve decarbonization in the FSC. Second, *Creating and reshaping markets* relates to political mechanisms aimed at establishing and regulating green technologies and products originating from low-carbon production processes. Third, *Knowledge creation and innovation* encompasses both public and private investments and initiatives toward low-energy and low-carbon technological transition. Fourth, *Building capacity for governance and change* addresses the creation of solid standards and principles to manage the challenges of consolidating decarbonized industries in the FSC across EU countries, which in turn, have diverse economic and social contexts. Fifth, *International coherence* underscores the importance of harmonized coordination in international spheres, able to design applicable tools based on

1 Estimation data from EDGAR: https://edgar.jrc.ec.europa.eu/.

regional capabilities and international commitments. Finally, *Phase-outs and socio-economic implications* discusses the impacts of transitioning to a sustainable, low-carbon food sector, highlighting differences among countries in their economic capacity to transition quickly and access sustainable food products.

The systematic collection of European initiatives from multiple stakeholders (Moreira-Dantas et al., 2022a,b) targets five main group categories: (i) *financial initiatives,* covering public and private investments spurring sustainability in the FSC; (ii) *industrial initiatives,* which refer to industry-specific collective action to enhance sustainability in operation systems; (iii) *policy and regulations,* which concern laws and governmental directives aimed at promoting sustainability in Europe; (iv) *food standards and ecolabels,* which support quantification strategies and methods for low-carbon food products; and (v) *consumer initiatives,* which comprise civil efforts by consumer associations and non-governmental organizations (NGOs) to promote sustainable food consumption in Europe. We have linked initiatives to each pillar according specificities and characteristics of stakeholders and initiatives found.

3. Results and discussion

In this section we present the main results concerning the interlinkages found for each of the aforementioned pillars and the collected initiatives by multiple stakeholders. The set of initiatives include a total of 27 financial mechanisms, 17 policies and regulations, 18 industrial and 13 consumer initiatives, and 18 eco-labels and standards. Figure 1 sets out a graphic representation of the linkages among pillars proposed by the industrial policy framework and the collection of initiatives from multiple stakeholders. *Directionality* is linked to policies and regulations, which offer a political guideline to decarbonize the food sector. *Creating and reshaping markets* is linked to financial mechanisms, food industries, and consumer initiatives. *Knowledge creation and innovation* is linked to financial mechanisms to foster research and development and innovation along the FSC. *Building capacity for governance and change* is linked to food standards and ecolabels, which provide guidelines to quantify food carbon footprint and other sustainable advancements. Lastly, *international coherence* and *phase-outs and socio-economic implications* are both linked to policies and regulations financial mechanisms and financial mechanisms. These initiatives and pillars interlinkages are discussed in sub-sections 3.1–3.6.

3.1. Directionality

Transitioning to a greener economy is amongst the joint EC priorities for 2023 and 2024 (European Commission, 2022), underscoring the EGD as a central political blueprint to the EU economy going forward. Although current political and investment plans to promote a healthy and sustainable European food sector set a new political paradigm, such aspirations have already been present in political agendas in the past. However, the previous attempts fell short due to the lack of policy integration and targeting mainly the agricultural sector over post farm-gate stages (Rayner et al., 2008).

Traditionally, policy directionality has been focused on the supply-side, where industry, governments and researchers were seen as key agents to determining and pushing for transformations (Schot and Steinmueller, 2018). For instance, Parks (2022) points out that directionality is a complex system having political guidance spurred by several levels of policy implementation. Nevertheless, designing political guidelines does not only imply putting in place stringent laws and regulations that mostly apply the supply-side, but also the integration of several demands, policies, and priorities across economic and regional contexts. From this perspective, advancing decarbonization strategies in the European food sector depends on a well-designed political framework. This should also be built in accordance with socio-economic, cultural and environmental conditions, and should facilitate investments in human capital to enable technological innovation, consumption stimulation, and production patterns aligned to political objectives. Related to this, the EGD and F2F strategy set the policy directions to attain a sustainable food sector, encompassing a series of strategies, regulations, and investment plans transitioning to a green production paradigm.

In the industrial arena, roadmaps play a crucial role in supporting political priorities (Saritas and Aylen, 2010), while providing guidance on technical issues when shifting to clean technologies and addressing steps to progressively decarbonize operations (Caritte et al., 2015). In this front, ongoing private efforts have resulted in the development of roadmaps, either focusing on general recommendations to decarbonize several economic sectors (e.g., Roadmap 2050,[2] Low Carbon Economy Roadmap),[3] or being sector-specific (e.g., Heat Roadmap Europe.)[4] Specifically, for the food industry, a roadmap targeting low-emissions in the food and drink manufacturing sector has been elaborated.[5] The latter notices that food and drink industries are not clustered in one location, but spread across geographical areas. On the one hand, this fuels the economic activity in a wider geographical outreach, but, on the other, it limits the technological access to centralized natural gas and hydrogen facilities. Additionally, the food sector is composed of several processes and products, highlighting the need for food-specific decarbonization processes, rather than a "one size fits all" framework applicable to other sectors.

In an ideal world, enacting policies and regulations should be complemented by evaluating policy efficiency and designing low-carbon interventions. This can be accompanied by industrial sustainability reports, which provide information of industrial emissions periodically and transparently. Nevertheless, corporate emissions data is limited, with variant quality, and does not cover several supply chains and SMEs (Busch et al., 2022). While analyzing the developments of energy generation in European countries, Aszódi et al. (2021) found that the existing energy strategies would preclude achieving the EGD's targets if no further action is taken. The authors argue that a harmonized mechanism is needed to consolidate clean

2 Roadmap 2025 is an initiative of the European Climate Foundation (ECF). Source: www.roadmap2050.eu/project/roadmap-2050.

3 European Commission Initiative to set out long-term strategy to reduce emissions. Source: www.eea.europa.eu/policy-documents/com-2011-112-a-roadmap.

4 Decarbonizing heating and cooling operation. Source: www.heatroadmap.eu.

5 Source: https://www.fooddrinkeurope.eu/wp-content/uploads/2021/09/Decarbonising-the-European-food-and-drink-manufacturing-sector_v2.pdf.

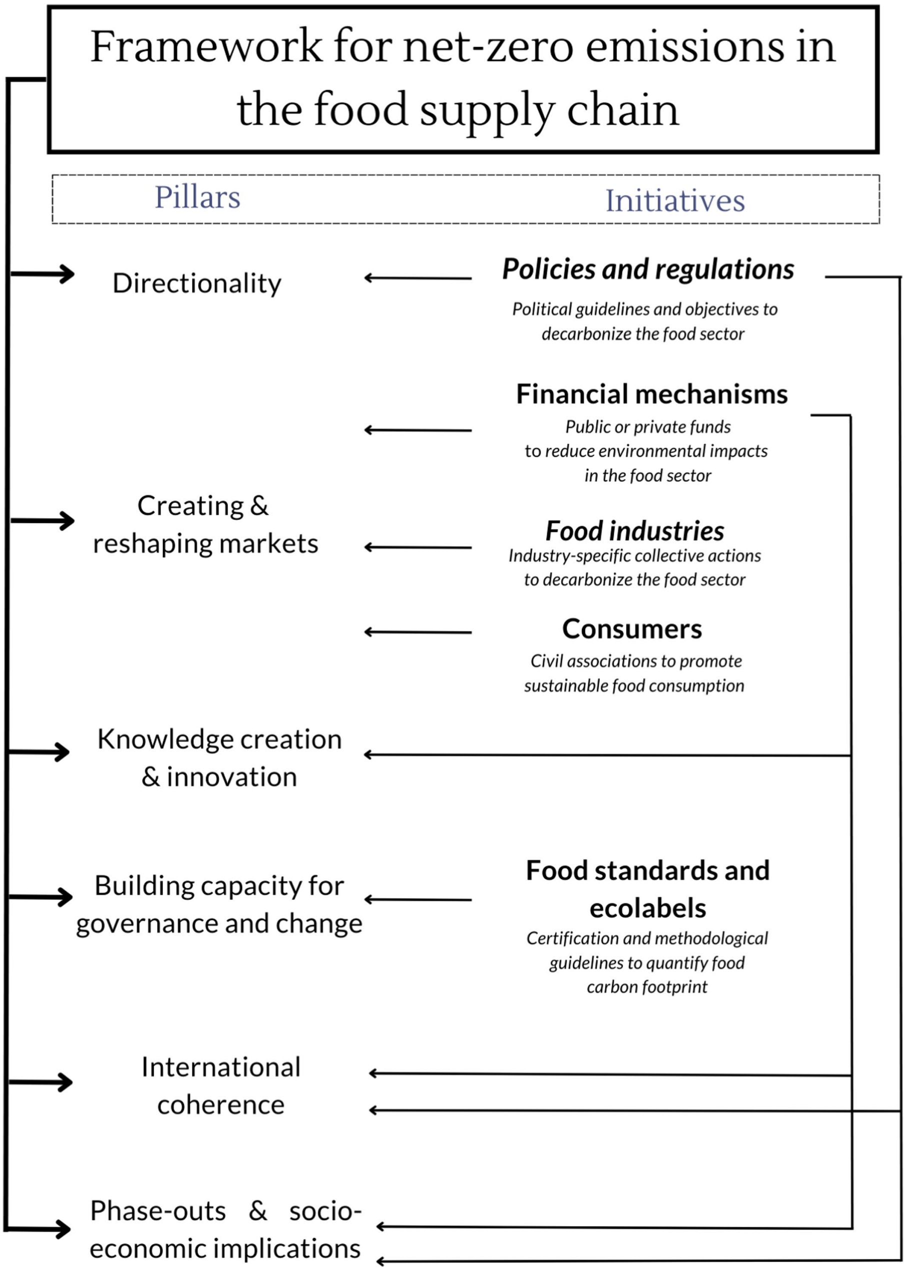

FIGURE 1
Conceptual framework with six pillars linked to multi-stakeholders' initiatives. Source: Authors' elaboration. Pillars are based on Nilsson et al. (2021) and the initiatives are proposed by Moreira-Dantas et al. (2022a,b).

energy sources (e.g., wind and solar power) and achieve the EU's 90% carbon reduction target.

In particular, the EU food sector must align with the shifts proposed by the EGD and F2F's political directions. To facilitate the already defined political objectives, the EC developed the "*Fit for 55*" plan, which revised climate and energy legislation and industrial objectives going forward. According to the European Council (2023), the proposed measures demand fundamental reductions in national specific GHG emissions from sectors not covered by the European Trade System (ETS), which include agriculture and waste management. EU members, with their own individual quotas, shall increase the share of renewable energy sources by at least 1,1% in the heating and cooling sector. Another measure is the Carbon Border Adjustment Mechanism (CBAM),[6] a tariff that will increase the price of imported goods in emissions-intensive sectors that are not produced under low-emission standards. Table 1 sets out a range of current proposals and regulations to reduce GHG emissions in the EU.

6 The CBAM Regulation entered into force on the 16 of May 2023 and the transitional phase, which only involves exchange of information, will start in October 2023: It will initially apply to cement, iron and steel, aluminium, fertilizer, electricity and hydrogen.

TABLE 1 Top-down directionality.

	All stages	Production only	Distribution only	Production, process, and distribution	Processing, distribution, and retail
Laws and regulations	– Farm to Fork Strategy – Legislative framework for sustainable food systems – European Climate Law – Investing in a climate-neutral future for the benefit of our people /2030 Climate Target Plan – The Renewable Energy Sources Directive – Proposal for a directive of the European parliament and of the Council on Corporate Sustainability Due Diligence and amending Directive (EU) 2019/1937 – The EU's current Effort Sharing Regulation (EU) 2018/842	– Amending Regulations (EU) 2018/841 – Sustainable product policy initiative – Global Methane Pledge	– Directive 2006/40/EC of the European Parliament and of the Council of 17 May 2006 relating to emissions from air conditioning systems in motor vehicles and amending Council Directive 70/156/EEC – Sustainable and Smart Mobility Strategy	– EU code of conduct on responsible food business and marketing practices – Proposal for a Directive of the European Parliament and of the Council amending Directive 2013/34/EU	– F-gas regulation – EU No 517/2014 of the European Parliament and of the Council of 16 April 2014 on fluorinated greenhouse gases and repealing – Regulation (EC) No 842/2006 – Eco-design Directive (Directive 2009/125/EC) – Energy Labelling Directive (Directive 2010/30/EU)

Laws and regulations setting sustainable food pathways to reduce greenhouse gas emissions along the European food supply chain. Source: Authors' elaboration based on multi-stakeholders' initiatives: Horizon 2020 ENOUGH project (Moreira-Dantas et al., 2022a,b).

These legal efforts are generally applied to specific productive sectors and may also include some stages of the FSC. The F2F is the central political strategy particular to the food sector, albeit with a general target across all the FSC stages. Regulatory proposals involving specific FSC stages are likewise applied to other productive sectors. By contrast, food production is the only FSC stage with proposals designed specifically for production activities. As an example of production-specific legislation, the "*Amending Regulations (EU) 2018/841*" is part of the Fit for 55 Plan aiming to increase carbon removals in the combined land use, forestry and agriculture sector at EU level by 2035. On the other hand, the "*F-gas regulation*" [Regulation (EU) No 517/2014] exemplifies a political enforcement applied in all sectors utilizing F-gases within the FSC and beyond. This regulation provides a mechanism to reduce F-gases by two thirds of the 2010 level by 2030, by progressively phasing down production and import of high global warming potential (GWP) refrigerants, banning high GWP refrigerants in new equipment such as fridges in households or supermarkets, air conditioning and foams and aerosols, and also in the servicing of such equipment. Additionally, F-gases emissions from existing equipment shall be monitored.

Table 1 presents the regulatory framework related to the difference FSC stages. It can be observed that the main environmental laws in the EU refer to all stages. While there are few regulations targeting single stages (e.g., production and distribution), others directives have a more general character and are applied to multiple stages collectively.

Although it is too early to evaluate the effects driven by these regulatory measures, the EU FSC will certainly undergo fundamental changes. The overall impact of such legislation will depend on factors related to company size, market integration, available investments, and national sector-specific political directionality. But energy-intensive operations in particular, such as processing, retailing, transport, and domestic energy use will bear increasing costs due to expected higher carbon prices. These higher costs could induce changes in the energy mix and foster investments in clean-technologies.

3.2. Creating and reshaping markets

In order to establish the conditions for creating and transforming markets suitable for green technologies, low-carbon products and processes, the necessary political mechanisms that regulate these markets have to be in place. Moreover, consumer engagement is essential to help shaping markets. In this sub-section, we first cover the policies and actions related to the supply side, followed by the demand side initiatives to create and reshape food-related markets in the EU.

From the supply optic, governments play a fundamental role in understanding investment conditions while prioritizing low risks, which is seen as the main barrier to a faster, cheaper, and lasting transition (Polzin and Sanders, 2020). Climate-friendly investments are imperative when seeking energy efficiency, adopting low-carbon technologies, and reducing overall GHG emissions (Hrovatin et al., 2016). Polzin (2017) argues that replacing fossil-based energy sources by clean technologies requires investments in both technology development and diffusion. Nevertheless, the majority of energy financing remains related to fossil-fuel based technologies, and overall funds for clean-energy have decreased in the past decade (UNEP, 2014; Andrijevic et al., 2020). By analyzing current ventures for clean energy in Europe, Polzin and Sanders (2020) suggest that the European financing portfolio is large enough to spur green-energy, however, there is considerable qualitative divergence regarding where the current investments are placed and where they are most needed. These authors found very few private small-scale equity funds for clean-technology research, development, and demonstrations. As a result, revamping financial strategies to solve the current financial gap and to foster green energy sources is timely (Pianta and Lucchese, 2020). In this context, private players tend to modestly invest in research and development (R&D), thus public funds should be allocated to technology developments that contribute to decarbonization (Hannon and Skea, 2014).

Coherence is then essential to ensure that applicable tools are available to enable different regions in achieving international commitments to decarbonize their food sector. The EU has collectively invested in international initiatives to endorse sustainability. One example is the EU Taxonomy Regulation, which is a classification system that defines criteria for economic activities that are aligned with the EGD. Its main objective is to support financing the sustainable transformation by directing investments to the economic activities most needed for the sustainable transition and aligned to the EGD goals (European Commission, 2023c). The EU Taxonomy serves (non-)financial initiatives and companies with a systematic classification of sustainable economic activities, thus scaling up investments and preventing green washing issues (European Commission, 2023c). Similarly, the Cohesion Fund supports environmental and transport infrastructure (TEN-T) in Member States with a gross national income (GNI) per capital below 90% of the EU average (European Commission, 2023d). Along with that, the systematic review on financial mechanisms shows 19 ongoing funds supporting international harmonization for a green transition (Table 2). While some of these funds cover all economic sectors, food decarbonization projects are eligible to receive investments.

To allocate enough investments to low-carbon R&D technologies, it is unlikely that capital will solely come from one source. Thus, diversifying investment funds can result in positive outcomes in innovation chains (Bumpus and Comello, 2017). Funds from private, governmental, and other financing measures (e.g., those having consumers involved) may support the green transition (Bürer and Wüstenhagen, 2009; Polzin, 2017). Yet, the defined carbon market adjustments and taxation should be accompanied by public reinvestment, so that the transition does not disproportionately impact certain players who may have fewer financial resources and market integration to comply with the new regulations. Pianta and Lucchese (2020) state that companies remain generally reluctant when it comes to further investment in green R&D, due to the high risk involved compared to potential financial return. The green transition should drive higher demand for sustainable goods and services, so that low-carbon technologies generate profits, jobs, and incomes (Pianta and Lucchese, 2020).

This scenario is not different for food companies, where most SMEs depend on external investment to update industrial plants to use low-energy technologies, natural refrigerants, and cooling and heating innovations. Financial stability is of core relevance to foster competitiveness and to afford high input and service prices. According to our systematic review, there are 27 financial mechanisms and 18

TABLE 2 Financial mechanisms to improve sustainability, decarbonization and energy efficiency.

Financial mechanisms	Period	Budget (Million Euros)
Adaptation for Small holder Agriculture Programme (ASAP)	2012 – ongoing	€ 900.0
Climate Action 100+	2017 – ongoing	€ 68,000,000.0
United Nations Environment Programme Finance Initiative (UNEP FI)	1992 – ongoing	€ 100,000,000.0
Programme for Environment and Climate Action (LIFE)	2021 – ongoing	€ 5,430.0
European agricultural fund for rural development (EAFRD)	2021–2027	€ 386,333,400.0
European Regional Development Fund (ERDF)	2021–2027	€ 200,360.0
Horizon 2020	2021–2027	€ 95,000.0
Just Transition Mechanism (JTM)	2021–2027	€ 19,200.0
Cohesion Fund (*CF*)	2014–2027	€ 392,000.0
European Green Deal Investment Plan (EGDIP)	2021–2027	€ 1,000,000.0
European Maritime, Fisheries and Aquaculture Fund (EMFAF)	2021–2027	€ 108,000.0
Recovery and Resilience Facility	2021–2026	€ 723,800.0
Blue Sustainable Ocean Strategy	2019–2023	€ 2,500.0
Joint Initiative on circular Economy	2019–2023	€ 10,000.0
S3FOOD	2019–2022	€ 5.0
The European Fund for Strategic Investments (EFSI)	2015–2020	€ 10,700.0
Investor Energy-Climate Action Toolkit	2018–2020	€ 1.5
Programme for Competitiveness of Enterprises and Small and Medium-sized Enterprises (COSME)	2014–2020	€ 2,300.0
EU Finance for Innovators (InnovFin)	2014–2020	€ 2,700.0
Total		€ 556,906,296.5

Source: Authors' elaboration based on multi-stakeholders' initiatives: Horizon 2020 ENOUGH project (Moreira-Dantas et al., 2022a,b).

industrial initiatives (Moreira-Dantas et al., 2022a) in place in the EU with the aim to financially support these stakeholders' stability.

Nevertheless, financial mechanisms are broadly designed, calling for proposals in several sectors and may be generally applied to all FSC stages. Funds are often provided by the European Investment Bank (EIB) or private initiatives. Generally, funds target projects related to research and innovation (R&I), R&D, the circular economy, and waste management systems in SMEs. Likewise, agriculture is a central activity covered by various investment projects to leverage agrotechnology, innovation, and rural development. While such investments are undoubtedly necessary, when combined with industrial initiatives they can potentially provide opportunities for tangible achievements. Industrial efforts financed either by private means or by public ventures are aligned to EGD objectives and aim to foster innovation and international cooperation to work on waste management and reduce agricultural emissions.

We observe a strong emphasis on the agricultural sector in terms of investments and industrial projects, which is not noticed in other FSC stages. Industrial initiatives were also classified according to a climate change approach (Figure 2). Most initiatives respond to climate change mitigation strategies, followed by those with a sustainability emphasis, but without a clearly defined scope towards climate change. Only a few initiatives are related to adaptation strategies but rather with a particular emphasis on food production. Overall, industry efforts to mitigate climate change are either applied to the agricultural sector or are related to all stages of the FSC.

From the demand side, consumer preferences of food and diet also play a significant role in shaping the market. Some consumers have already started to reshape tastes towards more plant-based diets (Protein Smart, 2021), which have lower carbon footprint than meat. For example, the carbon footprint of 100 g of protein from beef is on average approximately 6 times that of chicken, and 35 times that of beans (Poore and Nemecek, 2018). Typical alternative proteins include plant-based foods, insects, lab grown meat, and seaweed, among others (BBC News, 2021; HDI Global SE, 2021). The carbon footprint of alternative proteins is typically lower than that of red meat, which could contribute to emissions reductions especially in Asia where 60% of the global population is located (AFN, 2023).

The role of alternative protein for future food has been identified as a key factor that could affect cooling and energy demand, and therefore related GHG emissions. Some consider alternative protein for its sustainability or health-related benefits (Possidónio et al., 2021). However, there are various challenges to adopting alternative protein globally, which relate to social, behavioral, regulatory and technological issues. For instance, in terms of public perception, a survey of 1,930 adults in the UK showed that only 30% of respondents perceived lab grown meat as being safe, compared to 50% for edible insects, and 77% for plant-based protein (Food Standard Agency, 2022). In terms of regulation barriers, some lab grown meat has recently received clearance from the Food and Drug Administration in the United States (The New York Times, 2022), but not in the EU. If alternative protein and vegetarian-based diet become mainstream in the future, it could lead to significant changes in energy demand, cooling, cooking, and corresponding emissions globally.

In this regard, consumer initiatives are an important part of civil engagement to enhance sustainability awareness and to promote sustainable food consumption. As shown in Figure 3, EU consumers engage mainly in information transfer related to food origin, waste reduction, consumer rights, and the green transition for sustainable consumption. The EU highlights the importance of civil efforts to raise awareness about food sustainability and the implementation of appropriate sustainable practices according to local contexts (European Commission, 2017), while private and public engagement is related to the profitability of R&D results from mature and new technologies (Mathews et al., 2010; McCollum et al., 2018). In any case, the nature of initiatives that have been systematically collected indicates a higher emphasis on a single FSC stage (e.g., production). Thus, there is a need to increase the level of engagement in other stages of the FSC. Moreover, continuously integrating private and public actions is essential, so that stakeholders can communicate their current needs, identify limiting factors for technological transition, design interventions, and improve emissions reporting.

3.3. Knowledge creation and innovation

Research and innovation are the links between today's problems and future solutions in decarbonizing the food sector, which is amongst the emissions-intensive production sectors (Crippa et al.,

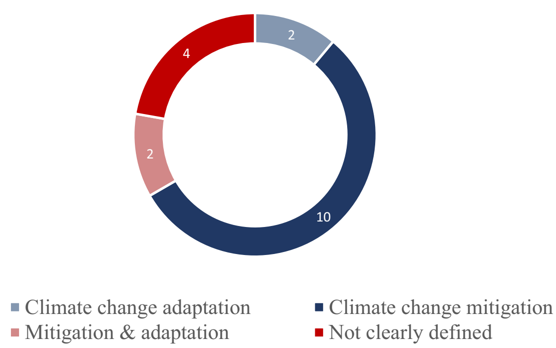

FIGURE 2
Number of industry initiatives according to climate change mitigation and adaptation strategies. Source: authors' elaboration based on multi-stakeholders' initiatives: Horizon 2020 ENOUGH project (Moreira-Dantas et al., 2022a,b).

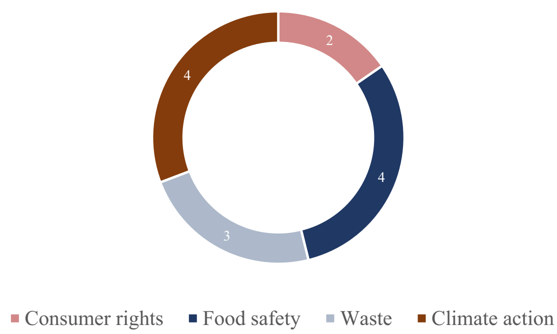

FIGURE 3
Number of consumer initiatives divided according to main objectives related to consumer rights, food safety, food waste, and climate action. Source: authors' elaboration based on multi-stakeholders' initiatives: Horizon 2020 ENOUGH project (Moreira-Dantas et al., 2022a,b).

2021). The challenge of building sustainability within the food sector involves multiple stakeholders and their perspectives, as well as various uncertainties and trade-offs (Riccaboni et al., 2021). This complex scenario demands solutions that consider all the interlinked needs of the food sector to respect the earth's limits to bear air pollution, especially regarding the decarbonization of its supply chain operations (Kok et al., 2019; De Froidmont-Goertz et al., 2020). Therefore, R&D is key to ensure efficient solutions that accounts for the FSC's complexity.

In the last three decades, R&D has made progress in tackling specific problems concerning the food sector, but with a narrow focus on increasing food availability at reasonable prices. This ensured affordable food to accompany a rapidly growing population, however, it did not solve nutritional challenges, biodiversity loss, and the significant GHG emissions throughout the sector (Garnett, 2013). In this scenario, actors from the entire FSC, from producers to the government, have a distinct importance in encouraging R&D focused on reducing GHG emissions and communicating where and how to innovate (Herrero et al., 2020; Riccaboni et al., 2021).

Riccaboni et al. (2021) reviewed recent R&I initiatives throughout the FSC, which were aimed at improving sustainability from primary production to consumption. Initiatives from farmers focused especially on the sustainable use of soils and their management. For example, the combined use of land for livestock and crops limits the overuse of nutrients, and precision agriculture techniques with sensor-based monitoring systems generate more efficiency and higher yields. Other business operators have innovative initiatives related to reducing food waste, integrating networks to improve processes, and empowering actors to choose more sustainable processes (Riccaboni et al., 2021). These actions of private actors must be accompanied by the effective involvement of not only policymakers but also of consumers and research centers (Riccaboni et al., 2021), considering that there are economic and social barriers to the adoption of these innovative techniques (Clapp and Ruder, 2020). The literature on technology adoption points to high-value enterprise farmers having a higher adoption rate while adoption is lower for small-scale farmers or for those located in distant areas (Bongiovanni and Lowenberg-Deboer, 2004; Groher et al., 2020; Bollington et al., 2021; Visser et al., 2021; Fuglie et al., 2022). For this reason, even though investment in international agricultural R&D has shown to generate high returns, innovation is key for the achievement of proposed sustainability milestones (Rosegrant et al., 2022). Thus, impacts vary depending on the focus of the research undertaken (Fuglie et al., 2022).

In line with this need to foster R&D and innovation, in 2014 the Horizon 2020 (H2020) program was implemented as part of the EU's Common Strategic Framework (CSF) for R&I. Its main goal was to finance R&I until 2020 with a total budget of around €80 billion. The projects are related to not only fostering innovation but also its applications to industry, covering various fields from agricultural and natural sciences to engineering, technology, and social sciences. Beyond this clustering, the domain of application is considered for the choice of projects as well. Figure 4 illustrates an analysis of the Community Research and Development Information Service (CORDIS) database by field of application, clustering projects that started after 2020 until 2027, and have some applicability in the FSC, which we called "food-related projects." We found a total of €1,2 billion addressed to Climate Change and Environment projects with 20% of this budget targeting food-related projects. Meanwhile, projects related to Food and Natural Resources received €85,4 million of investment with 54% of projects related to the food sector.

Among food-related projects under the Climate Change and Environment category, several supply chain stages received investments, as shown in Figure 5. Food production received 31% of the total budget directed to food-related projects in the category, followed by aquaculture and sustainable agriculture. Food-related processing and transport sectors, in turn, only received 2% of the budget, highlighting the unequal effort towards certain sectors of research.

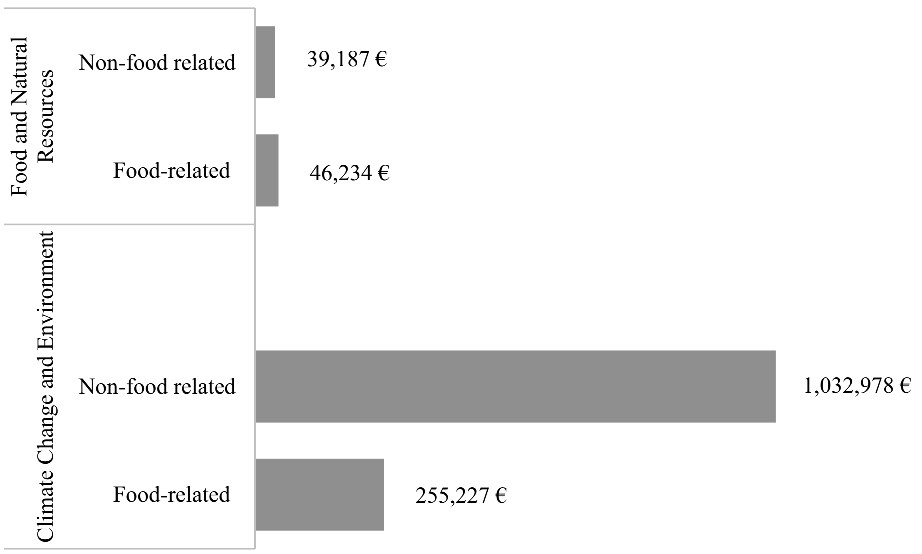

FIGURE 4
Distribution of food-related projects across domain of application (in € 1,000). Source: authors' elaboration based on: Community Research and Development Information Service (CORDIS). https://cordis.europa.eu/projects/en. Period covered: 2020–2027.

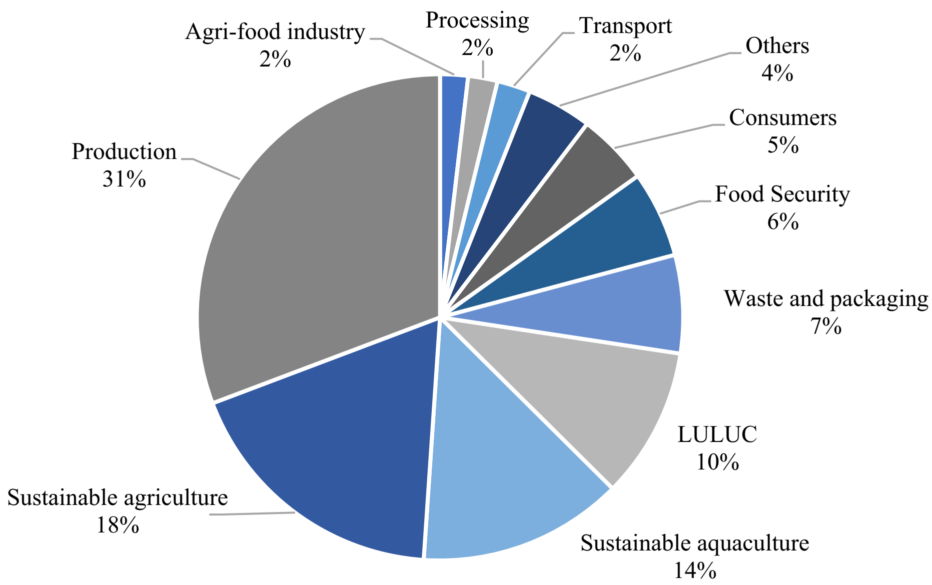

FIGURE 5
Distribution of food-related projects by domain of application across the Climate Change and Environment category. Source: authors' elaboration based on: Community Research and Development Information Service (CORDIS). https://cordis.europa.eu/projects/en.

From 2021 onwards, Horizon Europe replaced H2020 as the EU's key funding program for R&D and innovation, running until 2027, with a larger budget of €95.5 billion. It plays a central role to the Green Deal framework to tackle climate change, achieve the UN Sustainable Development Goals (SDGs), and ensure a low-carbon emission food sector (De Froidmont-Goertz et al., 2020), as the development of green technologies is crucial for the success of this challenge (Guo et al., 2020).

In the future, R&D and innovation should focus on harmonizing the many ongoing digital platforms, standards, and initiatives at the EU level. By considering the specificities of each context as a base for policy proposals and implementation, as well as a structure that enables science and society to work together toward solving complex societal challenges (Kok et al., 2019), it is possible to build data-driven solutions that are effectively achieving zero net carbon emission in the food sector (De Froidmont-Goertz et al., 2020).

3.4. Building capacity for governance and change

Political discussions to reduce GHG emission impacts date back to 1972 with the Meadows report, and took shape in 1992 during the Rio Earth Summit. These discussions have had notable effects on European policy-making (Hafner and Raimondi, 2021). More recently, the EGD has set even more ambitious goals for European countries to achieve carbon neutral economy. EGD's success depends, however, on structural changes that need to be coordinated across societal groups, with strong command and control of public and financial authorities (Pettifor, 2019). Moreover, technology and governance should act synergistically to transform the economy in the long-run (Pianta and Lucchese, 2020). In practice, given the urgent nature of the green transition, this represents a key challenge in consolidating a carbon-neutral EU.

The food sector deserves particular attention, as the FSC is composed by a substantially diversified set of companies (Moreira-Dantas et al., 2022a), all highly competitive, with access to formal and informal markets, and having different production realities (Vermeulen et al., 2012). The shift to clean energy sources and the implementation for energy efficient systems should be accompanied by technical knowledge integrated in a governmental capacity. This means that political institutions shall develop information tools to progressively monitor production systems, processes, their demands, and impacts. Additionally, informing consumers about a product's origins and processes can potentially influence market behaviour and the solidification of food produced under environmental standards. In this context, food-related voluntary certification and eco-labelling initiatives have increased in recent years. Non-governmental organizations (NGOs) together with industry associations have led a series of ecolabels in response to environmental concerns of consumers and activists' groups (Gulbrandsen, 2006). Ecolabels support sustainable consumption, and its adoption encourage producers to increase their environmental standards (Horne, 2009). The systematic collection comprises 18 fully designed food-related ecolabels and standards, which are described according to start date, supply chain stage and relation to climatic goals (Table 3). Most of them have a broad scope that encompasses all FSC stages, with strong emphasis on GHG monitoring and environmental impacts based on life cycle assessment.

More specifically, in the manufacturing of food and beverages, the EU approved the Eco-design Directive (Directive 2009/125/EC). This is a framework directive that obliges manufacturers of energy consuming products placed in the EU market to reduce energy consumption and, in some cases, other negative environmental impacts occurring throughout the product's life cycle. The Eco-design Directive is complemented by the Energy Labelling Directive (Directive 2010/30/EU), and the former is considered one of the most successful regulations applied in Europe. A recent report from the

TABLE 3 Food-related ecolabels and standards by date, supply chain stage and link to climate goals.

Name	Start date	Supply chain stage	Explain the link to climate goals
ISO 14067 greenhouse gases	2013	Entire supply chain	Principles, requirements and guidelines for quantification and reporting of carbon footprint in food products.
PAS2050	2011	Entire supply chain	Consistent internationally applicable method for quantifying product carbon footprints.
GHG protocol product standard	2011	Entire supply chain	Requirements to quantify the GHG products inventories.
The Product Environmental Footprint (PEF)	2012	Entire supply chain	Methodology that quantifies environmental impacts of product life cycle and would be supplemented with product category-specific rules.
4C association	2007	Production-Processing	Ensure compliance with sustainability criteria for coffee production and processing from the economic, social, and environmental dimensions to establish credible and traceable sustainable coffee supply chains. i.e.: No deforestation, climate change mitigation, use of renewable energy.
Pharmed responsibly ASC (Aquaculture Stewardship Council)-feed standard	2021	Production	Feed standard: identify energy sources, implement energy efficiency plan, and monitors GHG emissions.
LEAF (Linking Environment and Farming)	2012	Production	Monitor energy consumption and CO_2 emissions.
The planet-score	2021	Entire supply chain	The score is based on life cycle assessment and supplemented by additional indicators accounting for impacts (pesticides, climate, biodiversity and animal welfare).
Bonsucro	2005	Production	Principles and criteria for environmental responsibility, social development, economic return, and good industry practices.
Eaternity score	2014	Entire supply chain	Rates products by Climate Score, Water Footprint, Rainforest Score and Animal Welfare Score. It is based on life cycle assessments and rates from 1 to 3 stars (1 more carbon than the average) and 3 climate-friendly (50% less emissions than the average).
CO_2 measured – Carbon trust	2007	Entire supply chain	Measure the total product greenhouse gas emissions, from extraction of raw-materials, to end-of-life. It is measured in carbon dioxide equivalents (CO_2e). Labels: CO_2 Measured, Reducing CO_2, Carbon Neutral, Reducing CO_2 packaging, Carbon Neutral packaging, Lower CO_2, 100% Renewal Electricity.
Reducing CO_2-Carbon trust			
Carbon neutral – Carbon trust			
Reducing CO_2 packing – Carbon trust			
Carbon Neutral packing – Carbon trust			
Lower CO_2 – Carbon trust			
100% Renewal Electricity – Carbon trust			
Eco-Score		Entire supply chain	A benchmark score is established using data from the "AGRIBALYSE" environmental database. These data correspond to the life cycle analysis (LCA) of the products. It includes 14 environmental impact indicators: climate change/carbon footprint, ozone layer depletion, ionizing radiation, land, water, and energy use; pollution of air and marine and fresh water (particles, acidification, eutrophication); and depletion of resources.

Source: Authors' elaboration based on multi-stakeholders' initiatives: Horizon 2020 ENOUGH project (Moreira-Dantas et al., 2022a,b).

European Environmental Bureau (EEB) estimated that Eco-design could account for a third of the total emissions reductions needed to achieve the 55% greenhouse gas reduction target by 2030 (Schweitzer et al., 2021).

Eco-design covers several sectors of the refrigerated cold chain, namely, domestic refrigerators, professional (catering) refrigeration, commercial cabinets (termed cabinets with a direct sales function) and other areas of the cold chain though their use of air conditioners, lighting, water pumps, electrical motors and variable speed drives and fans. All these products are subject to minimum energy performance standards (MEPS) and most also apply energy labelling. Levels for the MEPS and labels are generated through preparatory studies that evaluate the market and suggest suitable levels to push the market to more efficient products. At regular intervals, the regulations are reviewed, and more stringent MEPS and labels are applied according to the market changes.

Several types of environmental impacts are considered within the Eco-design preparatory phase and include: (i) Material, energy and water resources; (ii) Waste; (iii) Emissions to air, water and soil; (iv) Hazardous substances; and (v) Physical impacts in the use phase. These impacts can occur in manufacturing, use, or at the end of the product's life. Although the Energy Labelling directive focuses on energy use, it can also cover the consumption of other resources and impacts, for example water consumption, noise levels during use, or the GWP of refrigerants. Currently, with most refrigeration equipment, the use phase has the greatest environmental impact and thus tends to be the focus of regulation. Generally, refrigerant leakage is not directly addressed in Eco-design as it is considered to be tackled via F-gas regulations (see above). Therefore, the focus is usually on MEPS and energy labelling (Bibalou et al., 2014).

The EU has also developed a 'Circular economy action plan' adopted in March 2020, which is one of the main parts of the EGD (European Commission, 2023e). The plan aims to make sustainable products the norm in the EU while halving municipal waste in Europe by 2030. It should have an impact on the entire food life cycle of products and aim to encourage the reduction of waste and promote circularity resource use. Much of the initiative related to food is targeting food waste, water use and general sustainability of food distribution and consumption.

Packaging is also targeted with the aim of increasing the use of recycled plastics and promoting more sustainable practices in plastic usage. Food packaging has important applications to sustainable food by addressing efficient resources use (Hellström and Saghir, 2007) and by reducing food and plastic waste (Guillard et al., 2018). Nevertheless, food packaging is related to several environmental impacts due to an oil-based production, the significant amounts of plastic produced within the EU, as well as plastic dispose and accumulation in soils and oceans (Jambeck et al., 2015; Guillard et al., 2018). In November 2022, the EU launched the proposal on EU Packaging and Packaging Waste Regulation (PPWR) with the primary aim to reduce package waste, revising the packages allowed on the European market, while protecting the environment and enforcing packages reuse and recycling (European Commission, 2023f). In an in-depth analysis of overpackaging impacts, FERN (2023) explain that with stringent reductions in plastic use, paper and paperboard are projected to be the main alternative for e-commerce, food packaging and overall packaging to replace plastic since those materials are primarily based on cellulose (Chen et al., 2013). The problem is that increasing paper demand will result in increasing environmental impacts in terms of water resources and forestry ecosystems in the global south (FERN, 2023). The report also states that high demand for paper packaging will need raw materials flowing not only from European forests, but also from countries such as Brazil, Uruguay, Chile and The United States of America. Considering that over 70% of paper production depends on virgin pulp and wood, reaching sustainable packaging in Europe can only be met if accompanied by strategies to halt negative feedback effects of current policies proposals.

The European Commission is also planning legislation on the right to repair products. The Eco-design Directive will be revised by the Sustainable Products Initiative, which was in public consultation until June 2021. The Sustainable Products Initiative aims to make products more durable, reusable, repairable, recyclable, and energy efficient as well as to provide end users with a practical means to self-repair their products or choose a third-party service provider instead of going through the manufacturer (European Commission, 2023g). Therefore, whereas previously EU initiatives have focused more on the end-of-life stage, the focus is now on the entire product lifecycle. Like the Eco-design Directive, the Sustainable Products Initiative will provide a general framework, and sector-specific legislation for different product categories (European Commission, 2023h). In addition, there is an intention to introduce an EU Digital Product Passport with information on components and their potential for recycling.

Another relevant regulation to the food industry decarbonization goals refers to F-gases. The European F-gas regulation has had a significant impact in reducing the use of fluorinated gases in Europe. A continual phase down of F-gas refrigerants has been applied since 2015 (Figure 6). Starting from an average GWP of 2,000, the allowed quotas will reduce the average GWP to 400 in 2030. The regulation is based on allowing a GWP quota into the market each year, and a cumulative and gradual reduction in the allowable quota. This has significantly reduced the F-gases available on the market and at certain stages increased the cost of high GWP refrigerants. Lower GWP refrigerants have entered the market with the increased use of natural refrigerants (such as carbon dioxide, hydrocarbons and ammonia) and the advent of ultra and low GWP synthetic hydrofluoroolefin (HFO) refrigerants (Kaschl, 2017).

An amendment to the regulation has recently been published (2019/1937/EU). The proposed new regulation is designed to strengthen the previous measures and introduce additional ones. In particular, the proposal is intended to enhance the ambition of the regulation by implementing a stricter quota system for HFCs which will reduce the HFCs placed on the market by 98% by 2050 (compared to 2015, based on $MtCO_2e$). It will also improve enforcement and implementation and apply harsher penalties for non-compliance. Monitoring will be more comprehensive with enhanced reporting and verification procedures. The proposed regulation includes HFOs alongside hydoflourocarbons (HFCs) for measures such as emissions prevention, leak checks, record keeping, recovery, and labelling. Much of the revision in the regulation is related to heat pumps and air conditioning systems, the use of which are projected to increase significantly in the future. Despite that, the stage in the food chain in which legislation related to refrigerants is lacking is that of transport refrigeration units (TRUs). For TRUs there are no product bans, but there are service bans precluding use of R404A (a refrigerator with a GWP of 3,922) in large systems (>10 kg). However, most TRUs use less than this, therefore the F-gas regulations[7] do not have much of an impact on reducing fugitive emissions in this sector.

3.5. International coherence

This fifth pillar emphasizes the relevance of harmonization and coordination in international spheres concerning the applicable tools to achieve decarbonization. Ideally, those tools must be based on regional capabilities and international commitments (United

7 Cold chain equipment such as domestic refrigerators, commercial hermetically sealed systems and large multipack centralised systems (>40kW) are already covered within the current regulation and have bans on the use of refrigerants with a GWP of >150 in new systems. The proposed revisions are passing through the European trilogue system which bring together representatives of the European Parliament, the Council of the European Union and the European Commission to discuss and agree legislation. The amendment was recently debated by the EU Council of Ministers who agreed to relax some of the bans originally proposed by the European Parliament. That the Parliament proposed a more stringent phase down is not surprising as they have a more ambitious phase down scenario than the Council of Ministers and European Commission.

Nations, 2008). The EU has been a major player in the world economy in terms of implementation of environmental regulations, and putting in place the necessary mechanisms that pave the way towards a low-carbon economy (European Commission, 2023i). The efforts of EU members shall be integrated to those of international partners to establish synergistic political and financial systems for sustainable development (Pinkse and Kolk, 2012). All EU countries have ratified the Paris Agreement and have presented their corresponding National Determined Contributions for a timely emissions reduction. But, although the EU is an important economic player, his actions do not suffice, other OECD countries and BRICS must also put in place decarbonization plans in order to avoid dramatic consequences in terms of climate change and biodiversity loses (OECD, 2015). Hence, a continuous and enhanced international coherence and collaboration is pressingly needed to achieve decarbonization in the framework of international agreements such as the Paris Agreement and the UNFCCC. While global agreements are outside the scope of this paper, this section focuses on EU initiatives that involve collaborations or coordination with other relevant players in the global economy.

The European Climate Law translates the EGD's objectives into long term laws and monitoring tools to not only decarbonize the EU economy, but also to make it irreversible (European Commission, 2023c). Siddi (2020) argues that to succeed, the green agenda must remain the main political priority in the long run. Additionally, EU institutions should coordinate and integrate financial resources and civil engagement in the direction of low-emission strategies, while international cooperation is indispensable to support the use of new clean technologies and sustainable markets, rather than continuously finance existing past technologies. Despite the recognized importance of the EGD premises, there is currently some resistance to adopt more stringent climate policies in the European Parliament. This is mainly due to high fuel and heating prices that consumers and companies must bear.[8] How these developments are going to be received by the EU citizens and national leaders, is still unclear. However, international compliance with global treaties and main goals (e.g., SDGs of which the SDG 13 urges to take action to combat climate change and its impacts) and European laws are the ways to adjust the green transition according to different economic realities.

In the food sector context, the path to achieve gains from transitioning to more sustainable production and consumption is complex, and green technologies emerge as an important tool for its success. While existing global models are considered inefficient for replicating a single country's experience without further adaptations (Mosnier et al., 2023), tailored solutions designed through international cooperation gained momentum in recent years. For instance, the Food, Agriculture, Biodiversity, Land-Use, and Energy (FABLE) Consortium was launched in 2017 as a collaborative initiative of international researchers and institutes. With 22 countries[9] in different continents participating in the initiative, its main goal is to develop consistent pathways toward global sustainability targets and trade harmonization. By grouping countries into six different profiles, according to their common food and land use systems, FABLE guides and helps countries to prioritize food and land use according to GHG emissions mitigation agenda (FABLE Consortium, 2023).

Beyond the integration of research and funding measures, it is very relevant to promote the transfer of green technologies from the global north, including the EU, to the global south. Guo et al. (2020) argue that the lack of worldwide criteria to classify green technology, which could enable GHG emissions reduction, is a barrier that prevents technology transfer internationally and contributes to a lack of investments in the field. The authors argue that green technology transfer is crucial to environmental protection and economic development of the world. This is especially because countries' capacities to access the newest green technologies on their own differ from non-industrialized to industrialized countries. Moreover, Karakosta et al. (2010) reinforce the importance of technology transfer to reduce countries' vulnerability to climate change, which is key to ensuring that food production will not be jeopardized and will follow sustainable processes.

The future calls for increasing levels of international coordination for policies that target long-term effectiveness and consider the country's capacities. The UN sustainable development agenda recognized both the need to fight climate change (SDG 13) (United Nations, 2023a) and strengthen global partnerships and goals implementation (SDG 17) (United Nations, 2023b). Climate finance falls short of about 100 Billion US$ dollars of commitment per year, of which 79.6 Billion is provided by industrialized nations (United Nations, 2023a). Nevertheless, ways to promote technological development, and to address the effects of carbon prices and trade policy initiatives still need to be clearly assessed. The integration of the SDG on the agenda of the multilateral trading system in the framework of the World Trade Organization (WTO) and of the negotiations of regional trade agreements (RTA), would mitigate local producers' concerns about losing competitiveness in international markets after adopting clean technologies. In this regard, the EU has been a pioneer in incorporating environmental provisions into RTAs, which reinforce the commitment of the ratifying countries to enforce their environmental regulations. Moreover, in 2022 the EU launched a communication (European Commission, 2022) to further enhance the contribution to sustainable development and consolidate the EU as one of the front-runners in this approach.

Finally, prioritizing the import of goods that are produced according to sustainability standards, working towards zero deforestation and biodiversity loss, and carbon neutrality processes would serve as an example for other regions (European Court of Auditors, 2021). These initiatives may follow and expand the example of sustainability standards already developed, such as the ISO 14067 which provides qualitative measures to classify a product's carbon footprint. Similarly, the Publicly Available

8 Financial times: Ambitious EU green policy reforms approved despite backlash | Financial Times (ft.com).

9 EU and non-EU members: Argentina, Ethiopia, Mexico, Sweden, Australia, Finland, Nepal, Turkey, Brazil, Germany, Norway, United Kingdom, Canada, India, Russian Federation, United States, China, Indonesia, Rwanda, South Africa, Colombia, and Malaysia.

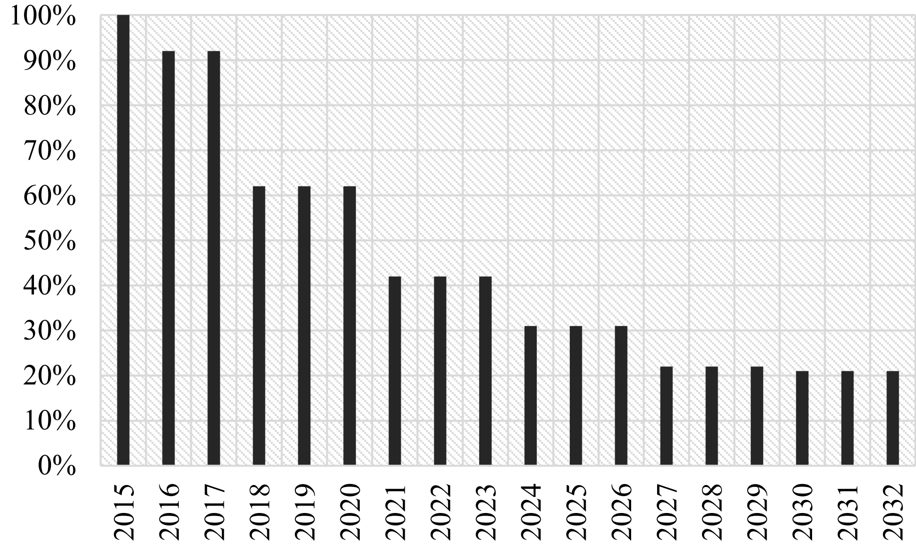

FIGURE 6
Current F-gas phase down. Source: authors' elaboration.

Specification (PAS) 2050[10] and the GHG Protocol Product Standard both are international initiatives that provide quantifying requirements of a product's GHG impact over its lifetime, affecting the entire FSC and collaborating to create an international food standard regarding emissions reduction.

3.6. Phase-outs and socio-economic implications

In the present framework, phase-outs of fossil fuel-based technologies in the food sector are important initiatives to guide a gradual transition in the direction of a low-emission system. Recent food-related policies phase-out soy and palm oil-based biofuel incentives in the transport sector and set regulatory reforms to accelerate the phase-out of routine uses of chemical inputs and pesticides (IPES-Food, 2019). The 27 EU member states also approved a global fossil fuel phase-out[11] to decrease GHG emissions by 2050, which also impacts the food sector through transportation costs.

The Renewable Energy Directive (RED II) approved a biofuels phase-out in 2018 for the post-2020 period, limiting the share of biofuels in Member States' renewable energy consumption, with the main objective of reducing the risk of indirect land-use related emissions and food scarcity (Mayr et al., 2021). Its provisions are related to those of the 2019 Internal Electricity Market Directive (IEMD) and Regulation (IEMR) and sets several new binding targets for the EU energy system (Hoicka et al., 2021). However, a side effect of the program is that international palm oil and soy producers will face significant economic disadvantages due to the trade implications arising from this regulation, which in practice acts as a technical barrier to trade. On the other hand, the measure will benefit European rapeseed producers by increasing demand for this product that was previously destined for oil production. Therefore, the specific consequences for the FSC go beyond the production nexus, considering the current global energy crisis, reducing the supply of biofuels could increase transportation costs and consequently lead to higher food prices (Trencher et al., 2022). Meanwhile, regulations to phase out chemical inputs and pesticides considered environmentally damaging have the potential to ensure soil and water protection, contributing to supporting organic farming and the introduction of organic fertilizers (European Environment Agency, 2022). The cost of this substitution could affect producers, especially the small and medium ones, increasing their cost of production. Thus, incentives must accompany the substitution to maintain the production costs at a level that will not decrease the food supply, such as conditional subsidies from the EU's Common Agricultural Policy (CAP).

In the EU, as well as in other countries, the full substitution of current technologies for cleaner alternatives will only be possible if this policy is accompanied by the cooperation of financial institutions and civil engagement. Eastern economies, whose production is primarily carbon based, are more resistant to technological change (Pianta and Lucchese, 2020). Existing financial mechanisms are therefore important to enable a just transition, where countries with lower economic advantage likewise pursue technological transformation. In any case, current investments under the Just Transition Fund and the EGD are not enough to finance an enduring systematic change (Storm, 2020). Moreover, the EU should continue to work towards a comprehensive industrial strategy to seek market integration, funding sources and fiscal policies that favor environmental investments, once the gaps of the current policies are identified.

10 PAS 50 www.ghgprotocol.org/sites/default/files/2022-12/GHG%20Protocol%20PAS%202050%20Factsheet.pdf

11 Energy prices and security of supply – Consilium (europa.eu).

4. Conclusion

This paper assesses the linkages between a general industrial policy framework and a set of current initiatives by multiple stakeholders that should pave the way towards net-zero emissions in the EU FSC. The framework comprises six pillars concerning policies, financing, R&D, R&I, governance capacity, international integration, and strategies to transition towards a green economy. We analyze within each pillar the interlinkages with specific initiatives in the context of the FSC in the EU. This analysis leads to a number of conclusions that are outlined in this concluding section.

First, in the political sphere, the F2F strategy and the EGD are the main blueprints to guide the green transition in the EU food sector. All stages, from food production to waste management, need to go through considerable transformations to promote the phase out of fossil fuels and GWP refrigerants when producing, transporting, cooling, and managing food products. When analyzing the directives, policies, and regulations, we observe that the political directionality is somewhat general and existing regulations are not designed to consider the specificities and challenges of FSC stages. Food production (including agriculture and land use change) is the only stage with proposals specifically designed for this sector. Considering the emission-reduction potentials of food packaging, transport, refrigeration, and consumption, more emphasis should be placed on the technicalities of stages beyond the farm gate. Moreover, monitoring tools to quantify corporate emissions data, in particular from SMEs, are still insufficient. The creation of a harmonized monitoring system is central to the development of an emissions benchmark, and in designing strategies to achieve net-zero emissions.

Second, climate finance is crucial to make clean energy sources and technologies more accessible. Yet, there is some divergence regarding where current investments should be allocated. Although investments that target R&D and technology demonstrations should be prioritize, there is insufficient investment in these fields. Meanwhile, the green transition should promote a higher demand for sustainable goods and services, so that low-carbon technologies generate profit, jobs, and incomes. When assessing the EU R&D projects under the Horizon 2020 program, we identify an unequal distribution of investments and industrial projects across FSC stages. Food production received 31% of the total investment directed to food-related projects in the category of climate change, followed by sustainable agriculture and aquaculture. Food-related processing and transport sectors, in turn, only received 2% of the budget.

Third, the EU faces a significant challenge in integrating its member states into a common goal, especially ensuring that those with economic disadvantage can likewise replace carbon-based technologies with clean alternatives. It is essential that the EU is aligned with international agendas (Paris Agreement, SDG, UNFCCC, etc.), to integrate international players, programs, markets, and trade agreements to support a long-term transition. Moreover, the green agenda shall be an enduring process along which investments are redirected to clean technologies, while attaining to regional contexts. In order to achieve this goal, coordination with producer and consumer initiatives is valuable and opens up a set of opportunities not only to communicate the importance and impacts of sustainability, but also to involve civil society in this process. Consequently, following this path demand for sustainable food products and services can potentially increase and incorporate further adjustments. Indeed, the initiatives in place already show a growing engagement of civil society in promoting awareness about food origin, health, and waste management. Likewise, food ecolabels and standards are valuable tools in guiding and informing consumers about the impacts of products. The projected harmonization of these standards should help increase awareness and support their effectiveness, as they are an integral to the transformation of markets.

Finally, an analytical exercise covering all FSC stages must still be conducted, wherein political rounds acknowledge technical and political gaps in every FSC stage, especially regarding financing, R&D, technology demonstrations, civil engagement, jobs generation, and market opportunities.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

IM-D: conceptualization, data collection, data analysis, paper analysis, draft, and revision. IM-Z: conceptualization, data analysis, paper analysis, draft, and revision. MA: paper analysis and draft revision. JE: draft and revision. AF: draft and revision. XW: draft and revision. MT: data collection and data analysis. SJ: data collection and data analysis. MM: data collection and data analysis. All authors contributed to the article and approved the submitted version.

Funding

Enough – European Food Chain Supply To Reduce GHG Emissions By 2050. This project has received funding from the European Union's Horizon 2020 research and innovation programme under the grant agreement no 101036588. We also acknowledge support by the Open Access Publication Funds of the Göttingen University.

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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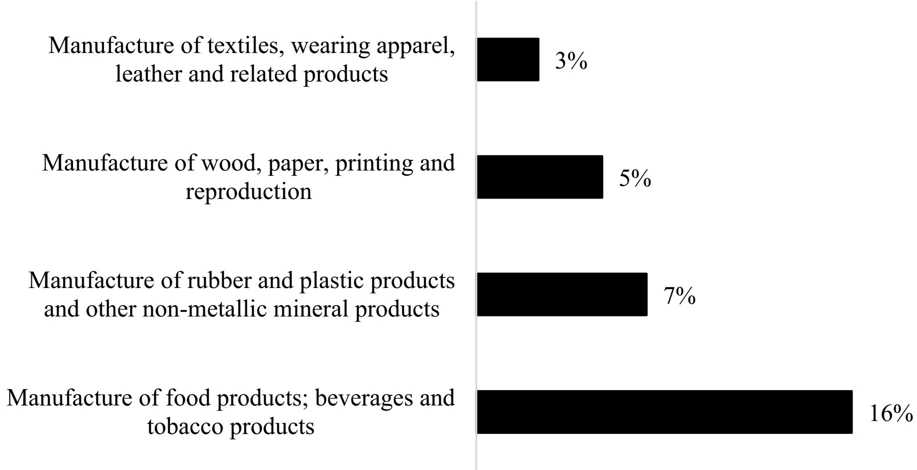
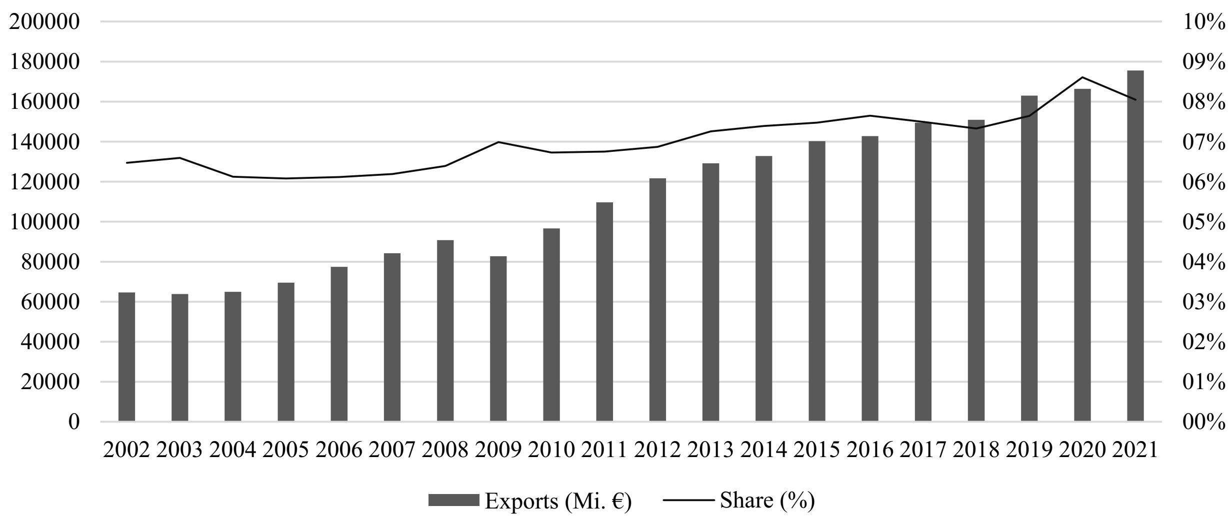
Appendix

Figure A1. Output share of manufacturing industries in 2020 in the European Union.



Source: Eurostat www.ec.europa.eu/eurostat/web/main/data/database. The United Kingdom is excluded.

Figure A2. EU food, drinks and tobacco exports to Extra-EU countries and share on total merchandise export.



Source: Eurostat www.ec.europa.eu/eurostat/web/main/data/database. The United Kingdom is excluded.