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Research

Impact of food waste reduction on food security and sustainability in the European Union

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Abstract
Food insecurity persists even in high-income regions such as the European Union (EU), where more than 88 million tons of edible food are wasted annually. This study explores the relationship between food waste reduction and food security within the EU's sustainability agenda, particularly the European Green Deal. Using a qualitative methodology, including a literature review and secondary data analysis from sources such as Eurostat, the Food and Agriculture Organization of the United Nations, and Our World in Data, we identify critical drivers of food waste – chiefly at the consumer level – and assess the environmental, economic, and social implications. Our findings indicate that reducing food waste can significantly enhance food availability, reduce greenhouse gas emissions, and preserve water and land resources. Interventions such as food banks, cold chain technologies, regulatory reforms, and support for local food systems are effective solutions. The study underscores the need for integrated policy frameworks that align technological innovation, consumer education, and circular economy principles. The study concludes that reducing food waste is not only an environmental priority but also a socioeconomic necessity for ensuring long-term food security, especially despite climate change and supply chain vulnerabilities.

Keywords circular economy · food waste reduction · food security · Green Deal · local food system · sustainability

1 Introduction

Hunger remains one of the most urgent and persistent global challenges. Although people often associate hunger with developing countries, high-income regions – such as the European Union (EU) – are not immune to food insecurity, malnutrition, and related social vulnerabilities. This realization has become particularly relevant as the EU embarks on one of the most ambitious transformation processes in its history, seeking to overhaul its food system as part of a broader shift toward sustainability and climate neutrality [1,2].

Recent theoretical advances in food waste reduction necessitate moving beyond traditional single-discipline approaches toward integrated systems frameworks. Building on emergent research in multicriteria decision-making for food waste management [3,4]. we propose an Integrated Sustainable Food Waste Reduction System that synthesizes circular economy principles, multicriteria decision analysis, and behavioral systems theory [5]. This framework addresses critical gaps by completing social impact assessments of stakeholders, ensuring that they are comprehensive, and by measuring efficiency an aspect that previous work often overlooked.

In recent years, global concerns about the resilience of food systems have intensified because of growing pressures from climate change, demographic shifts, political instability, and increasingly fragile supply chains. Researchers and policymakers now regard food insecurity, once considered a challenge of the Global South, as a structural issue across the EU. Persistent inflation, energy shortages, global market disruptions, and the aftermath of the COVID-19 pandemic have exposed the interconnectedness and fragility of modern food systems [3,4].

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The EU has committed to becoming climate neutral by 2050 through the European Green Deal. A key component of this strategy is the transformation of agrifood systems to reduce greenhouse gas (GHG) emissions, enhance resource efficiency, and promote sustainable consumption patterns [6]. Policymakers have further advanced these objectives through the Farm to Fork Strategy, a comprehensive initiative within the Green Deal that seeks to ensure healthier diets, provide fairer economic returns along the food chain, and substantially reduce food loss and waste.

The COVID-19 pandemic further exposed supply chain vulnerability and accelerated behavioral shifts in food consumption [7]. Many consumers turned to locally produced foods, however, increased household food purchases also led to rising levels of food waste. In high-income settings, food losses are most prominent at the consumption stage, often in the form of plate waste [8,9]. Retailers also contribute to this problem by promoting overconsumption and discarding unsold but edible products prematurely [10,11]. To address food waste at the retail level, a range of intervention strategies has been proposed, encompassing technical, marketing, and redistributive measures. Technical measures may include optimizing storage conditions, such as lowering refrigeration temperatures to prolong product shelf life [12]. Marketing approaches can target consumer behaviour by promoting the purchase of suboptimal products at discounted prices [13]. In addition, donation and redistribution schemes for unsold food items to charitable organisations represent an effective means of diverting edible products from waste streams while addressing social needs [14]. Overall food waste rates in supermarkets are estimated to range between 1% and 2% of total sales volume [15,16]. However, these proportions can be considerably higher for specific product categories, reaching up to 9% for fruits and vegetables and approximately 5% for bread [16,17].

Recent estimates suggest that approximately 88 million tonnes of food are wasted annually in the EU, with significant variation across Member States [18]. In parallel, [19] analyse the application of the food waste hierarchy within EU legislation, underscoring the importance of prioritising prevention over other waste management strategies. Its reduction is a critical objective not only for mitigating the environmental footprint of food systems [20] but also for enhancing their overall economic efficiency [21]. Beyond environmental and economic dimensions, food waste constitutes a pressing social and ethical concern. This is particularly evident in high-income countries, where food poverty persists[22] and unsustainable consumption patterns are frequently linked to the generation of waste [23,24].

These developments underline the need for a deeper understanding of the drivers of food insecurity and waste in the European context. Empirical evidence suggests considerable variation across member states. Western and Northern countries generally demonstrate strong food security, whereas Eastern and Southern states face greater nutritional risk. The pandemic further widened these disparities, particularly in countries such as Bulgaria, Romania, and Greece [25].

Additionally, major differences in per capita GDP across the EU directly influence household purchasing power and access to food. Countries such as Luxembourg and Ireland significantly exceed the EU average, while several Eastern member states lag behind [26,27]. War, inflation, and climate shocks have increased food price volatility, which in turn has intensified economic pressure across all stages of the supply chain. Data from the FAO Food Price Index show significant real price increases since 2020, reflecting heightened vulnerability and economic stress [28].

To address these challenges, policymakers need a regionally sensitive, data-driven approach to tackle food insecurity and waste in the EU. In this study, we integrate empirical insights on undernourishment, food insecurity, income disparities, and price dynamics to demonstrate the urgent need for coordinated, evidence-based policy action that supports sustainable and equitable food systems. Within this framework, household-level interventions represent a critical lever for change, as reducing food waste at the consumer stage can be achieved by strengthening perceived capabilities and routines, alongside information campaigns that target social norms and attitudes [29].

This study explores the role of food waste reduction in strengthening food security and enhancing sustainability within the EU. It examines how various interventions – technological, regulatory, and behavioral – can contribute to reducing food waste across the stages of the food supply chain and how these efforts align with the strategic objectives of the European Green Deal and Farm to Fork Strategy.

Beyond synthesising prior evidence, this article operationalises the EU food-waste/food-security nexus by introducing an integrated policy-economy-food-security lens that specifies how EU instruments (Green Deal, Farm to Fork, CAP) act through macroeconomic modifiers (purchasing power, price shocks, crises) to influence stage-specific interventions; presenting a policy-intervention typology with evaluation metrics that decision-makers can apply across member-state contexts; and stating testable propositions that move the literature toward falsifiable, mechanism-based explanations rather than descriptive lists. We use this lens throughout the Results and Discussion to interpret cross-country patterns.

The primary research questions related to the objective were organized into four thematic clusters to ensure a structured and comprehensive analysis. This approach allowed for a broader and more coherent exploration of the food waste–food security nexus while providing a clear analytical framework to synthesize findings and derive policy-relevant insights. The four focal areas and their guiding questions are as follows:

(1) Food waste levels and drivers: This cluster focuses on identifying where food waste is most prevalent in the supply chain and its causes, as well as exploring effective intervention strategies.

RQ1: *Which stages of the food supply chain generate the most waste, and what are the primary causes?*

RQ2: *What interventions (e.g., food banks, cold chain technologies, and consumer awareness) are most effective in reducing food waste?*

(2) Structural links to sustainability and EU policy: This group of questions addresses how efforts to reduce food waste align with EU sustainability objectives and highlights current policy limitations.

RQ3: *How does food waste reduction align with the goals of the EU Green Deal and the circular economy?*

RQ4: *What are the current policy gaps and challenges in implementing effective food waste reduction strategies at the EU level?*

(3) Food security implications and regional disparities: This section explores how reducing food waste can improve food security and how vulnerabilities vary across EU member states.

RQ5: *To what extent does food waste reduction contribute to improving food security in the EU?*

RQ6: *What socioeconomic and environmental factors influence food insecurity in the EU?*

RQ7: *How does food security vary across EU member states?*

(4) Economic disparities and consumption patterns: The final cluster focuses on the relationship between income, economic indicators, and food waste or insecurity.

RQ8: *How is food waste linked to income levels and per capita GDP in EU countries?*

2 Materials and Methods

This study applies a qualitative systematic literature review methodology aligned with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. The aim was to synthesize empirical and theoretical findings on food waste reduction, food security, and sustainability in the context of the EU.

In the exploratory phase of our literature analysis, we consulted Google Scholar and PubMed to support the development of the bibliometric network visualization. For the subsequent systematic review following the PRISMA protocol, however, we restricted the search to the Web of Science database in order to ensure methodological rigor and reproducibility. We processed our secondary data from relevant databases such as the FAO, the Statistical Office of the European Union (Eurostat), and Our World in Data. To support the analysis of food insecurity and economic disparities within the EU, we developed a set of visualizations based on recent and publicly available datasets. The primary objective of these figures was to identify regional differences in food-related vulnerabilities and to highlight how these intersect with macroeconomic and nutritional indicators across member states. Secondary data sources were included in our research, such as FAO and Our World in Data, using the most recent harmonized data available. To check food security in the EU, certain data were selected, such as the prevalence of malnutrition, undernourishment rates, food affordability indices, and per capita GDP. To visualize and interpret these data, we used descriptive statistical techniques and heatmaps generated via Excel and R Studio. Given the special nature of the examined topic, carrying out a sufficiently thorough analysis without the diverse methods used would have been impossible. Qualitative research methods are especially common for examining the practical implementation of various theories, as complex questions can be answered through their application. Qualitative research makes it is possible to determine whether the practical implementation of individual theories is successful and why (or why not) [30]. In relation to qualitative research results, the extent to which achieved results can be generalized is always a question [31]. Document analysis is a frequently used qualitative research method. In this case, a specific document is analyzed according to a specific set of criteria and compared with other documents [32].

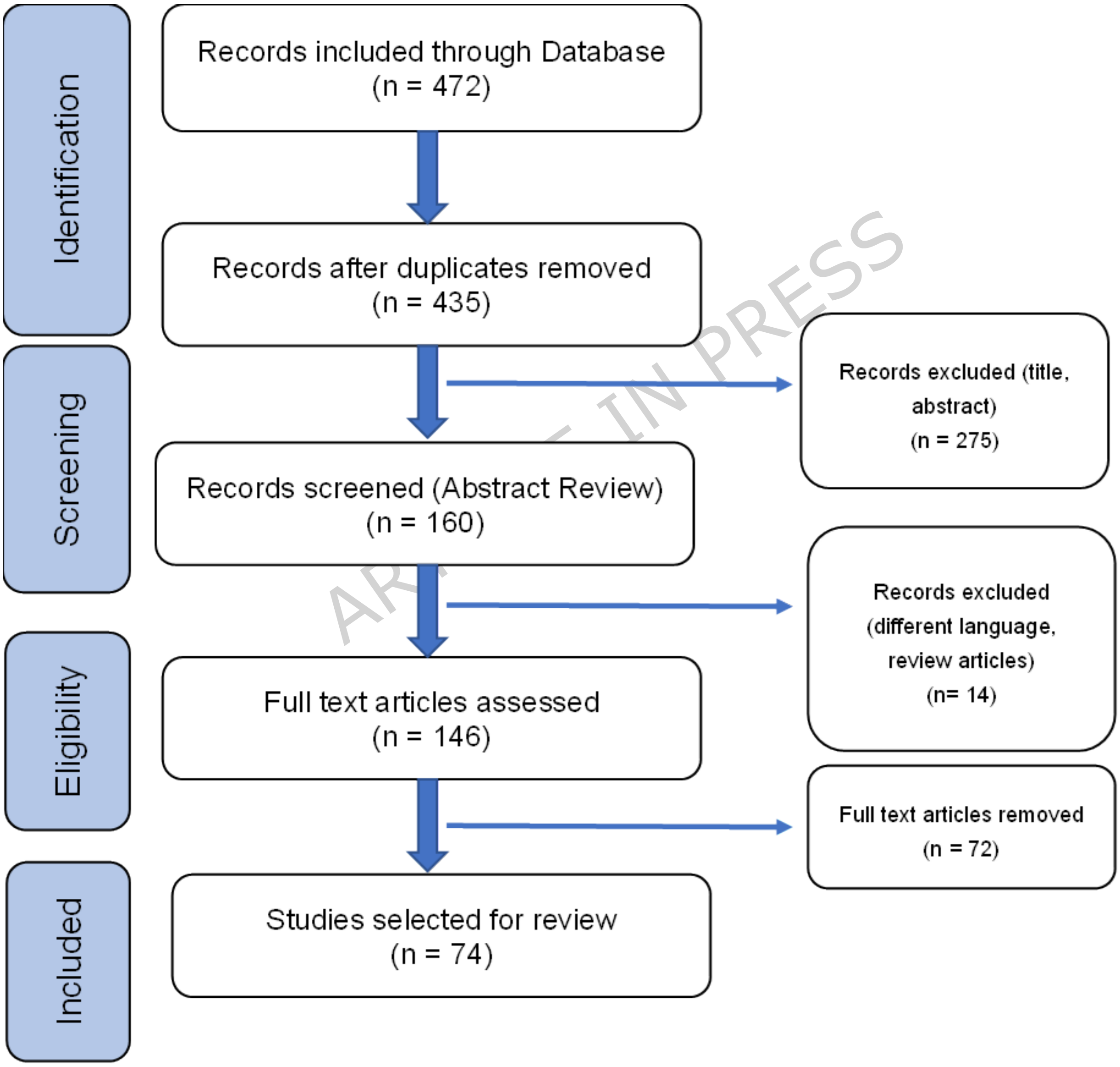

Fig. 1 PRIZMA model

Source: Own editing, 2025

This study conducted a systematic literature review following PRISMA to explore the link between food security and food waste/loss among EU member states (Fig. 1.).

The main search was conducted in April 2025 using four academic databases, including Web of Science. The Boolean search terms were the following (see Fig. 2):

- (“food waste” OR “food loss”) AND
- (“food security” OR “malnutrition”) AND
- (“European Union” OR “EU”) AND
- (“Green Deal” OR “sustainability” OR “climate change”)

The inclusion criteria were peer-reviewed articles, EU relevance, publication between 2000 and 2025, and English-language availability. We identified 472 records; after removing 37 duplicates, 435 remained. Of these, 160 titles and abstracts were screened, and 146 full texts were reviewed. A total of 74 articles were included in the synthesis.

Although no formal scoring tool (e.g., CASP, MMAT) was used, all studies were assessed for methodological clarity, data transparency, and alignment with the research questions. Priority was given to peer-reviewed work and credible institutional sources (e.g., FAO, Eurostat), and only studies with coherent, well-supported findings were included. We acknowledge that the lack of formal instrument and inter-rater reliability assessment is a methodological limitation.

During the screening process, we applied a structured checklist that we developed, assessing: (i) relevance in the EU context of food waste, food security and sustainability; (ii) clarity of research objectives; (iii) transparency of data sources and methods; (iv) appropriateness of methodology; (v) discussion of limitations and mitigation of bias; and (vi) policy relevance of conclusions. In the case of borderline cases, studies that were partially relevant or lacked sufficient methodological detail were reviewed jointly by the authors, and inclusion decisions were based on whether the study made a significant contribution to the policy-food security-macroeconomic integration perspective of the review. If this could not be identified, it was not included in the selection system.

A thematic content analysis was conducted on the selected articles. Coding was performed inductively to identify patterns related to food waste drivers, intervention strategies, and policy implications. To strengthen the quantitative rigour of our review, we systematically categorized the included studies according to their primary intervention type. The extended categories to the entire pool of 472 screened abstracts, we found a consistent pattern: regulatory/policy approaches (n = 110), economic/pricing interventions (n = 71), technological solutions (n = 70), behavioral/education (n = 42), food bank/redistribution (n = 8), and cold chain interventions (n = 2), while a substantial share of abstracts (n = 169) had no specific intervention focus. In the focused synthesis of 74 articles, the majority addressed regulatory and policy-related approaches (n = 28) and technological (non-cold-chain) solutions (n = 15), followed by behavioral and educational interventions (n = 12), economic instruments (n = 10), and food bank or redistribution strategies (n = 3), with only one study explicitly analyzing cold chain interventions. A smaller set (n = 5) had no clear intervention focus, but they were really crucial in the case of our topic.

These descriptive statistics provide a transparent quantitative layer to our qualitative analysis, confirming that regulatory, economic, and technological interventions dominate the literature, whereas cold-chain and redistribution strategies remain underrepresented. While the heterogeneity of study designs precluded a formal meta-analysis, these comparative counts strengthen the empirical foundation of our findings.

To complement the literature review, we gathered statistical data from FAO, Eurostat, and Our World in Data. These datasets covered food waste volumes, prevalence of undernourishment, food insecurity rates, and food price indices (2005–2023). The data served to triangulate findings and visualize macrolevel trends across the EU. This multimethod approach ensured both conceptual depth and empirical validation, enabling a robust understanding of the food waste–food security nexus in the European context.

3 Results

To address the research objectives and questions outlined earlier, the following section presents the main findings derived from the systematic literature review, thematic analysis, and complementary statistical data analysis. The results provide insights into the current state of food waste generation, food insecurity trends, and structural and behavioral drivers shaping these phenomena within the EU. Visualizations based on secondary datasets – such as Eurostat, FAO, and Our World in Data – support the interpretation of key indicators, including malnutrition prevalence, food insecurity levels, and food price dynamics. These results contextualize the challenges and potential policy pathways for reducing food waste and enhancing food system resilience in line with the European Green Deal and the Farm to Fork Strategy.

To explore the conceptual landscape of the literature, a bibliometric co-occurrence network was generated using VOSviewer (version 1.6.20) (Fig. 2). The keyword search combined the following terms: “food waste” OR “food loss”; “food security” OR “malnutrition”; “European Union” OR “EU”; and “Green Deal” OR “sustainability” OR “climate change.” The final network comprised 143 items grouped into seven thematic clusters and interconnected by 3446 links. The association strength normalization method was used to set the visualization parameters, with an attraction value of 6 and a repulsion value of 5. The resulting map reveals a high degree of conceptual linkage among the core themes and highlights dominant research fronts focused on food security, consumer behavior, circular economy strategies, and EU sustainability policies. This network visualization provides a structured overview of the academic discourse and serves as a useful tool for identifying key clusters, thematic convergence zones, and potential research gaps within the field of sustainable food systems in the European context.

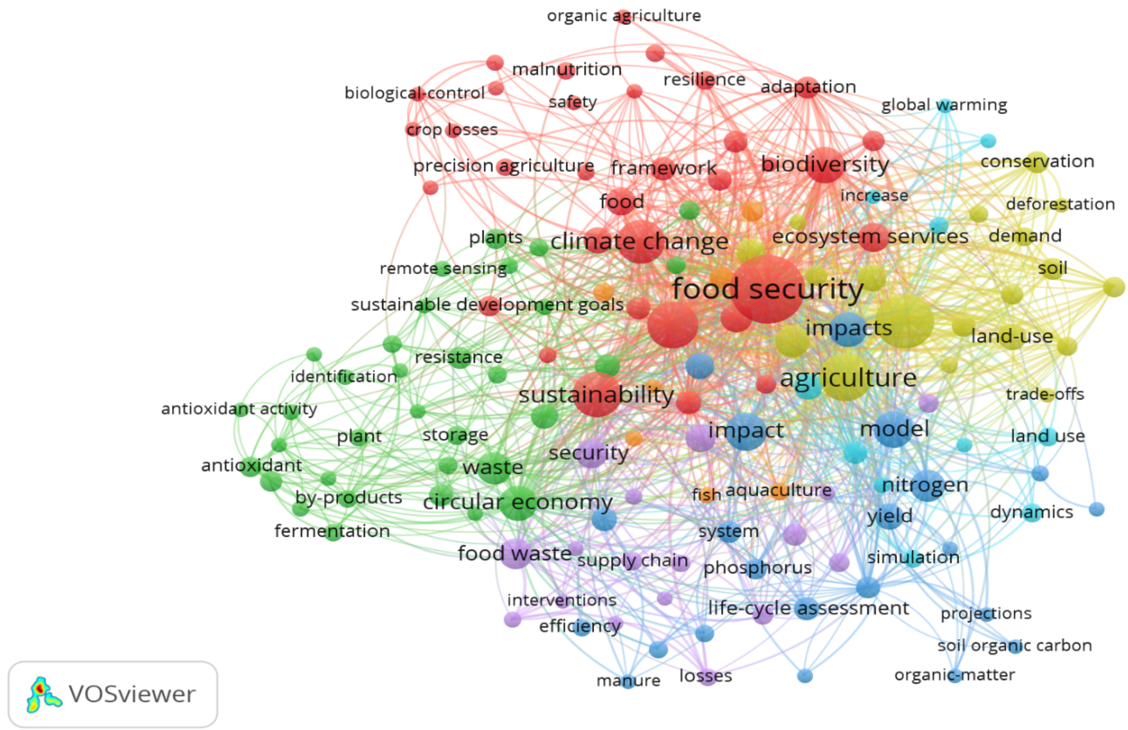

Fig. 2 Network of connections based on the presented keyword search

Source: Own editing with VOSviewer based on WoS[33]

The bibliometric network visualization highlights three dominant thematic clusters. The first cluster focuses on consumer behavior and household practices, the second on circular economy and recycling strategies, and the third on food policy and sustainability regulation. Although these areas are well represented, research on redistribution, cold chain logistics and regional inequalities in Eastern and Southern Europe remains scarce. This imbalance highlights a strong focus on consumer-oriented solutions, while structural and infrastructural interventions are relatively neglected an important research gap with direct implications for EU policymaking. This pattern also reflects our methodological decision to narrow the scope during the PRISMA screening phase: the initial search was intentionally broad, returning an extensive range of articles, but during subsequent refinement, we excluded several peripheral or related works to ensure relevance and methodological consistency.

3.1. Levels of food waste and drivers

In 2022, global food waste reached 105 million tons, representing 19% of consumer-available food waste at retail, catering, and household levels. Households accounted for a significant share of this waste, closely linked to income levels . Nonetheless, affluent and less affluent countries alike contribute to the problem [8].

Food waste significantly undermines food security and sustainability, making it a major global concern and it affects our move toward a circular economy. In the EU, excessive food loss interrupts the resource efficiency goals of the Green Deal. It also weakens attempts to provide fair access to food. Therefore, cutting down on waste is not only an environmental need but also essential for creating strong, circular food systems. According to the FAO, people waste approximately one-third of the food they produce each year [34], although exact estimates vary depending on whether we measure by quantity or value. Food waste can be cut down several ways, however, modifying consumer behavior, industry norms, and awareness campaigns are prioritized over systematic measures [35,36]. Household food waste has repeatedly been linked to behavioral determinants such as motivation, opportunity, and ability [29]. One way to effectively reduce food waste is through programs such as food banks, which repurpose food to assist those in need [37]. Reducing food waste can significantly impact global food security and ecological sustainability. Reducing food waste significantly enhances global food security and ecological sustainability. By cutting food waste, we also lower GHG emissions, as decomposing food generates methane, a potent GHG [38]. Additionally, reducing food waste alleviates the strain on natural resources [35]. Advances in cold chain technology and biotechnological interventions can reduce food losses during storage and transportation [39,40]. Although limited mobility during the COVID-19 lockdown reduced global GHG emissions, obesity rates increased in wealthier countries, whereas malnutrition worsened in poorer regions [41]. Obesity and global warming share a complex relationship: higher atmospheric temperatures reduce adaptive thermogenesis and physical activity, but carbon dioxide emissions remain high [41]. Sustainable agricultural practices and modern breeding technologies can also boost crop yields and minimize food waste [42].

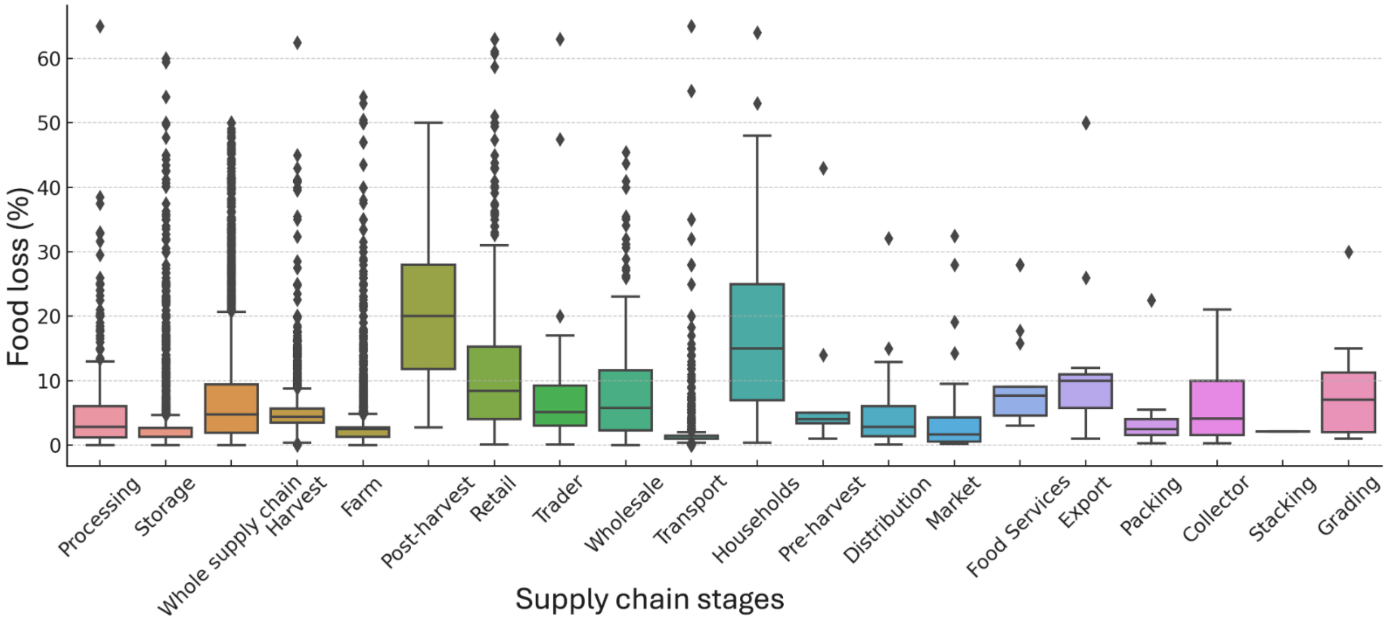

Fig. 3 Food waste levels by supply chain stage, 2000-2024 (boxplot)

Source: Own editing, based on FAO [28]

Fig. 3 illustrates the percentages of food waste globally for different stages of the food supply chain. The highest food waste occurs during the “Consumption” stage, indicating that final consumers are the biggest contributors. This underscores the importance of addressing household-level waste to reduce overall food waste. Significant waste also occurs during “Postharvest Handling and Storage” due to losses during food storage and handling. This stage is critical, as food is often wasted before reaching processing or consumers. While waste at the “Processing” stage is significant, it is generally lower than consumer-level waste, suggesting that reducing waste during processing is important but more manageable. The “Distribution” stage sees moderates but notable waste due to packaging, transport, or logistical issues. This analysis highlights the need for action across all stages to reduce food waste, especially at the consumer level, where the greatest loss is experienced. Improving resource efficiency and reducing environmental impact is essential for sustainable food supply systems [28].

3.2. Structural links to EU policy and sustainability

3.2.1. The European Union and the Green Deal

The EU is one of the regions most committed to the fight against climate change. By 1992, it had adopted its first climate change strategy, and in 1996, it set the goal of keeping global warming below 2°C compared with preindustrial times [43]. In 2001, with the effective cooperation of enough EU member states, the Kyoto Protocol was ratified and entered into force as a result. In 2005, the Emissions Trading Scheme started operating in the EU; it is the world’s most important GHG emission quota trading system [44]. In addition to such antecedents, the EU, as a federation of states, possesses a significant openness to issues of environmental protection.

According to the objective of the New Green Deal, GHG emissions must be significantly reduced in the EU by 2050, thus achieving the level of a society with net zero GHG emissions. For example, the draft intends to radically reduce GHG emissions in the industrial and transport sectors. It also requires a kind of social attitude change, the essence of which is the implementation of efficient resource use [45], which naturally includes food production and the food supply operation of chains. The border closures ordered due to the COVID-19 pandemic, especially during the spring wave of 2020, severely affected globalized supply chains, drawing attention to the strategic importance of local capabilities in the production of food. The economy of the EU, following the downturn due to the epidemic, a new, green intends to rebuild with an approach [46]. At the same time, the goal of the European Green Deal is to achieve much more ambitious changes: in addition to protecting the environment, its goals include creating a society that operates in a fairer way and is capable of development [47].

The European Green Agreement partly contributes to the development of sustainable food systems by reducing food waste, which accounts for other dimensions in addition to increasing food security and reducing hunger [48]. Reducing food waste directly affects food security by increasing the amount of food available and reducing hunger, especially in underdeveloped regions [49]. About 88 million tons of food are wasted in the EU every year, equivalent to 173 kilos per person. This not only wastes resources but also contributes to climate change. The EU Parliament is working on new measures to reduce food waste in the EU by 50% [50]. The aim of the European Green Deal and the related "Farm to Fork Strategy” is to reduce food waste; doing so will contribute to the development of more sustainable food systems and improve food security. Reducing food waste not only reduces the environmental burden but also increases the amount of available food, thereby directly influencing hunger reduction. Such measures are important for achieving the UN’s Sustainable Development Goals, which include ending hunger and ensuring the sustainability of food production [51]. The strategy approaches the objective of sustainable food production holistically and places great emphasis on promoting sustainable food consumption. In this context, it strives to minimize food loss and aims to minimize the amount of waste generated, with sustainability playing an ever-increasing role in the processing and distribution of food [52]. According to an announcement by the European Commission, however, the creation of the "Farm to Fork Strategy" was also necessary because consumers show an increasing commitment to healthy eating; one result from this is that healthcare expenses can be significantly reduced [53].

At the same time, the European Green Deal includes not only the switch to carbon-neutral production [46,54] but also the digital transition, which – in addition to strengthening knowledge transfer – has a prominent role in the modernization of agricultural production and thus in sustainably increasing food production, i.e., reducing the number of hungry people [55]. The modernization of food production and food supply cannot be postponed because approximately half of the total GHG emissions, as well as more than 90% of water stress situations and the loss of biodiversity can be attributed to the extraction of raw materials, as well as the processing and production of various materials, fuels, and food. Accordingly, the level of food waste must be reduced to make progress in using used resources, which is a priority area of the EU Circular Economy Package [56]. The seriousness of the situation and the importance of the topic are justified by the fact that in 2006, an average EU citizen living in the EU-27 member states wasted 179 kg of food, amounting to 180 billion euros. In addition, about 30% of all food produced – together with all the resources used and emissions generated during its production – was never consumed by any human being. Food waste alone is responsible for 3% to 5% of the overall effects of global warming and for more than 20% of the pressure on biodiversity, while the production of wasted food has tied up approximately 30% of global cropland [57]. Based on 2021 data, the amount of food waste in the EU was 131 kg/person, of which 70 kg/person (54%) came from consumers [58]. Resource waste has a significant impact on the environment and, paradoxically, while agriculture suffers greatly from the effects of global climate change, it is itself responsible for their development [59]. Considering the listed data, the establishment, development, and maintenance of the food bank system is critically important because food waste can be reduced with the help of food banks, i.e., fewer resources, such as water, are needed to feed the population [60]. Approximately 65% of the entire amount of food waste generated in Europe comes from five countries, namely Germany (10.92 Mt), France (9 Mt), Italy (8.65 Mt), Spain (4.26 Mt), and Poland (4 Mt), totaling 36.83 Mt. Thus, Italy and Poland rank third and fifth, respectively, among the European countries that waste the most food. Food waste amounted to 146 kg per capita in Italy and 105 kg per capita in Poland [61].

When decision-makers consider the issues of future food supply, they must consider several factors. The first of these should be the productivity and biomass production potential of the various soil types. The characteristics and limitations of soil types can have a significant impact on how and to what extent individual agricultural areas around the world can play a role in the global food supply. When considering conditions, it is also necessary to keep in mind how certain external environmental effects, and above all the effects of global warming, will change the state of soils in the future [62]. In view of this, it is inevitable that in the future European regions will increasingly prepare action plans related to local climate change, in which they describe what each region plans to do to reduce the extent and effects of climate change and how they plan to meet all the challenges that future changes will generate [63]. The ability to adapt to the effects of climate change is another factor that decision-makers must remember when planning the future food supply. However, [64] emphasizes that one of the most important objectives of the European Green Deal is to maintain the safe, nutritious, and high-quality nature of European food [64]. To do this, the quality of the soil must be preserved, and soil pollution must be avoided under all circumstances. A cornerstone of internationalized food trade is to avoid the eventual deviation of food safety standards, i.e., food safety rules should be unified as much as possible so that the consumption of produced foods can be decided according to uniform rules [64,65].

One of the most important objectives of the EU is that production processes, including food production, should have the smallest possible environmental impact. To this end, productive activities involving GHG emissions are taxed, which is naturally reflected in the consumer price of products produced in this way. As a result, the EU must levy such taxes on products imported from third countries that cause GHG emissions during their production, as a result of which additional costs are associated with import as if the given product had been produced within a territory of the EU. In the absence of such regulations, price-sensitive consumers within the EU internal market would prefer to buy products imported from countries where environmentally harmful production is not penalized by the local government, and in addition, EU companies using more expensive environmentally friendly production technology would be at a competitive disadvantage within the internal market [66]. According to a Dutch study, if Farm to Fork comes into effect, European grain production would be 10% to 20% lower on average. At the same time, there is a risk that due to increased prices, more food would come in from outside the EU [67]. At the same time, it is clear that today we must fight global warming with a combination of economic measures related to production and consumption. Although measures such as taxation are appropriate, they are not sufficient to minimize negative environmental impacts [67]. As a result of growing consumer interest, traders are increasingly sharing the characteristics of the products they sell, including in the agrifood sector, while economic actors are also developing solutions to prevent problems along supply chains caused by the impact of COVID-19. As part of this, traders with larger cash reserves can play a more significant role in guaranteeing the security of the supply [68]. In parallel, food surpluses have occurred as a result of the institutional closures introduced during the COVID-19 epidemic, especially the closure of institutions that also provide public catering, such as schools. Those food producers who sold their products in canteens were suddenly left without a market, and they cannot sell their supplies in the retail trade for several reasons, such as, for example, the lack of an established network of contacts. In the United States of America, where the level of food waste was already high, closures due to COVID-19 caused the level of food waste to increase by an additional 30%, even though 40% of the food produced was already wasted before the epidemic [69]. As a result of the COVID-19 pandemic, almost all countries have introduced various measures to ensure the population's access to safe, healthy, and sufficient food and to remedy potential operational challenges in the primary sector. Humanitarian interventions introduced in the field of food supply are primarily typical of developing countries [70].

3.3 Food security implications and regional disparities

3.3.1. Global and regional drivers of food insecurity in the 21st century

Malnutrition and food insecurity have been on the rise worldwide in recent years despite the UN's goal of ending hunger by 2030 [71]. Malnutrition, in all its forms – including undernutrition, micronutrient deficiencies, and obesity – has become a leading contributor to global morbidity and mortality [72]. Poor dietary quality and unhealthy nutrition are key drivers of the rising prevalence of overweight and obesity, especially in low- and middle-income regions, where access to healthy food remains limited [73].

The root causes of food insecurity are complex and multifactorial. Economic slowdowns and recessions – further aggravated by the COVID-19 pandemic – have severely disrupted food production, distribution, and household purchasing power [74-76]. Conflicts and political instability, such as the ongoing Russian–Ukrainian war, have led to food supply disruptions, trade restrictions, and volatile food prices [77]. A study further observed that pandemic-related lockdowns reshaped household food management practices, with mismanagement accounting for over half of avoidable waste in Europe [78]. These tensions are compounded by inflation, fertilizer shortages, and energy crises, all of which directly threaten the pillars of food security: availability, access, utilization, and stability [79].

COVID-19 had far-reaching impacts on global agriculture and food systems, reducing labor availability and transport capacities and reshaping consumer behaviors during lockdowns [80,81]. Dietary patterns have shifted toward more processed and shelf-stable foods, often leading to worse nutritional outcomes [81]. These cascading global crises underscore the urgency of aligning policy responses with the European Green Deal, the Farm to Fork Strategy, and the new Common Agricultural Policy (CAP) [82]. These frameworks aim to enhance the resilience of the food system, reduce vulnerability to external shocks, and support equitable access to safe, nutritious, and sustainable food across the EU and beyond [83,84].

3.3.2. Empirical insights into food insecurity, economic disparities, and price trends in the European Union

Fig. 4 helps in understanding the malnutrition situation in different parts of the EU and highlights the regions where further attention may be needed. Western and Northern European countries such as

Austria, Belgium, Denmark, Finland, Germany, the Netherlands, and Sweden show low malnutrition rates, and these rates are stable over time.

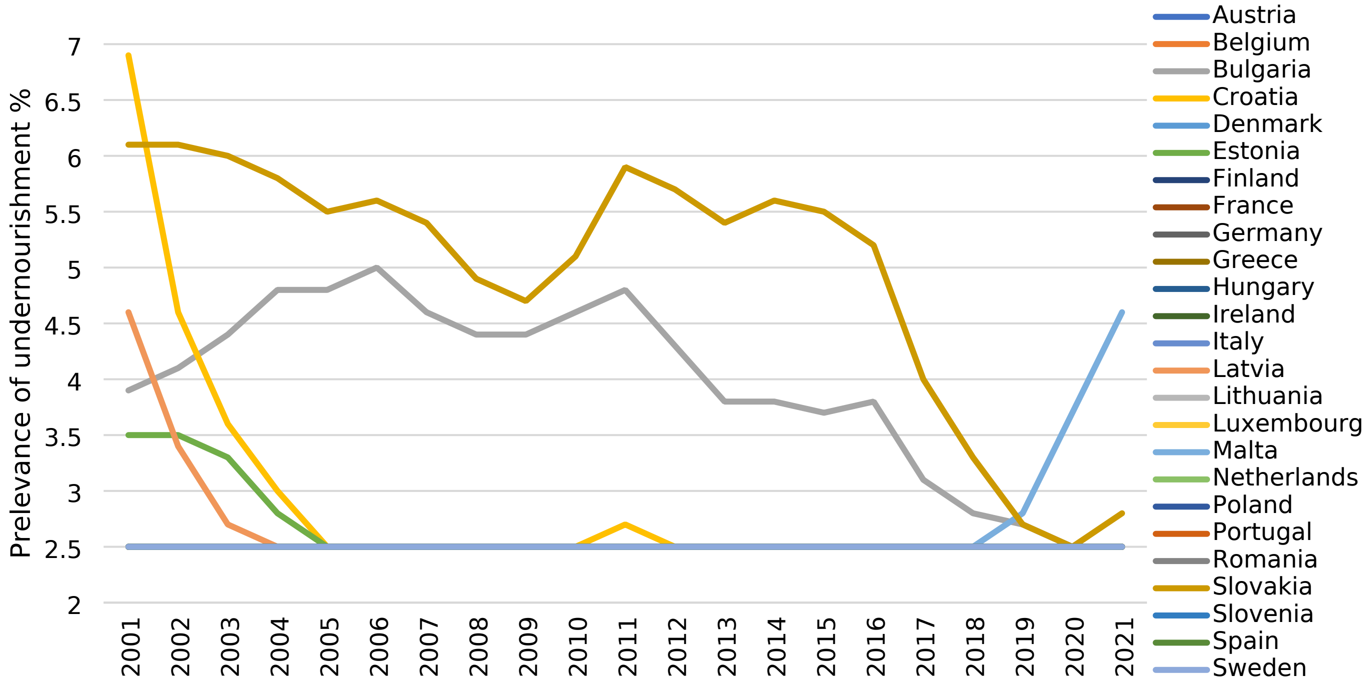

Fig. 4 Prevalence of undernourishment in EU countries, 2000-2022

Source: own editing based on Our world in data[85]

This indicates good food security and a stable economic situation. Countries such as Bulgaria, Romania, and Hungary show a downward trend in the prevalence of malnutrition, which may indicate an improvement in nutrition and food safety. Smaller fluctuations are observed in some countries, such as Greece and Italy. It is clear that the rate of malnutrition varies by country, but in the majority of EU member states, the rates are favorable and low. In Southern Europe, Greece and Spain experienced heightened food insecurity during the COVID-19 pandemic—Greece reported moderate to severe food insecurity rates between 6.6% and 8% during 2019–2022, exacerbated by the financial crisis and the pandemic [86], while in Spain the economic downturn left many low-income households unable to afford food, relying on emergency aid and even going without meals to feed their children [26].

Fig. 5 Prevalence of undernourishment in EU countries, 2000-2022 (heatmap)

Source: Own editing based on Our world in data[85]

The previously presented data are shown using a different approach in Fig. 5. This heatmap effectively visualizes the rates of malnutrition in different EU countries over the years. It helps in recognizing differences between countries and changes over time, highlighting areas where additional attention may be needed to improve food security. Darker cells denote higher prevalence. Cross-country differences co-vary with income levels (see Fig. 7) and the policy environment described in Section 3.2: higher-income countries implementing robust demand-side measures sustain consistently low rates, while lower-income countries show greater volatility. Countries such as Romania and Bulgaria display greater year-to-year variability than the EU-15 average, indicating more volatile progress toward undernourishment reduction. Western European countries such as Austria, Belgium, and Germany show stable values over the years, which indicate a stable economic and social situation. Determining maximum and minimum malnutrition rates by country can help identify periods when problems were most severe.

A key pattern in Fig. 5 aligns with income differentials: member states with higher real GDP per capita (see Fig. 7) sustain persistently low undernourishment, whereas lower-income members show higher dispersion and occasional reversals. This suggests that economic capacity conditions the access dimension of food security. In policy terms, countries with broader adoption of Farm to Fork demand-side measures (e.g., consumer education, clearer date-labelling, donation incentives) tend to maintain lower and more stable undernourishment levels, while states emphasizing CAP Pillar II investments in storage and local infrastructure appear to reduce upstream losses but still face access-related constraints during shocks. Cross-referencing Fig. 7 (GDP per capita) and the policy frameworks discussed in Section 3.2 strengthens this interpretation.

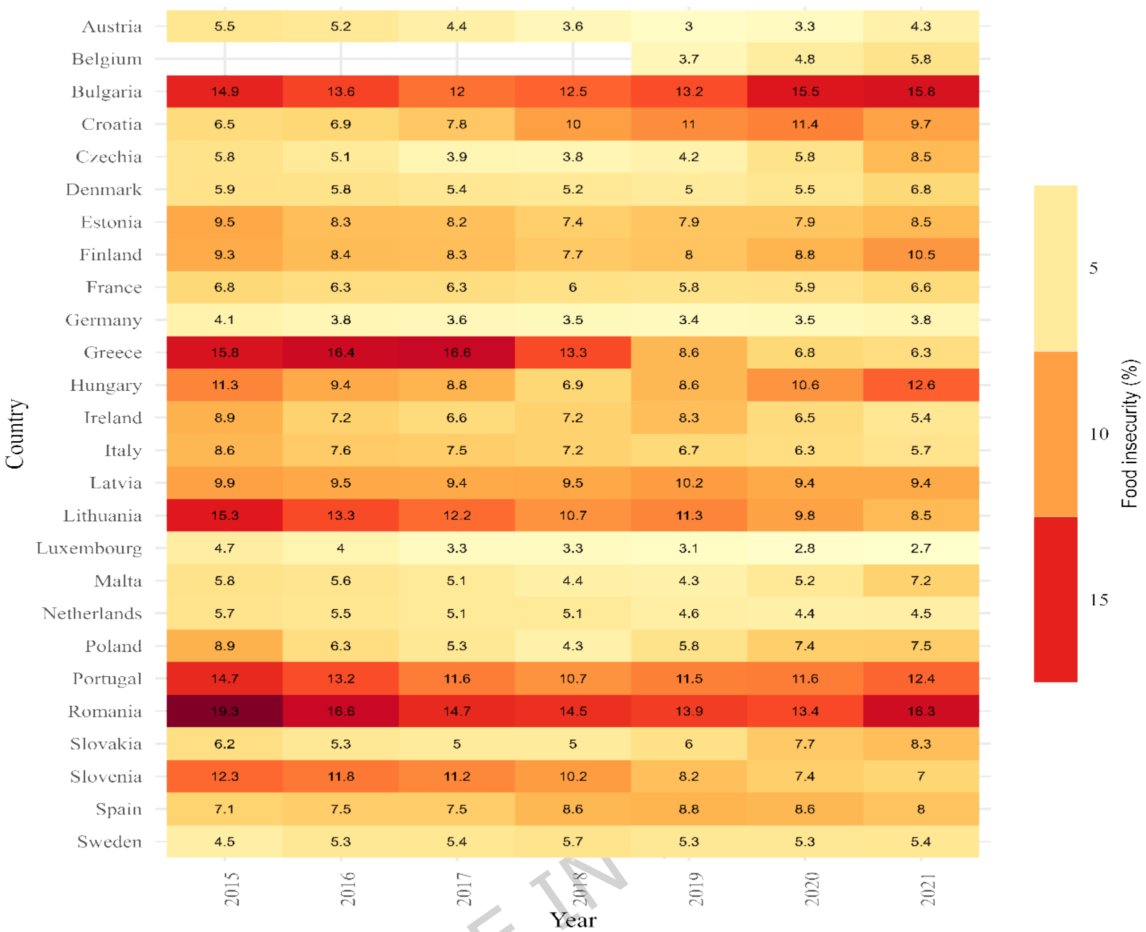

Fig. 6 Prevalence of moderate or severe food insecurity in EU countries 2015-2021 (heatmap)

Source: Own editing based on Our world in data[87]

Fig. 6 shows the prevalence of moderate to severe food insecurity in EU member states over the years, highlighting differences between countries and trends over time. Bulgaria and Romania show higher rates of food insecurity, indicating economic and social challenges in these regions.. Western and Northern European countries, such as Austria, Germany, and Sweden, have low food insecurity rates, reflecting more resilient household access and stronger social protection. Temporal patterns in Fig. 6 rise around 2020–2022, consistent with food price pressures shown by the FAO Food Price Index (Fig. 8) and Eurostat food price indicators (Fig. 9). These spikes primarily affect the access pillar of food security via reduced affordability. Countries that rapidly expanded redistribution networks and donation incentives, clarified date-labelling, or activated targeted income supports dampened these spikes more effectively than those without comparable measures. This linkage between price shocks, policy response, and household access clarifies why some member states experienced brief, contained increases while others saw prolonged elevation. The effects of the COVID-19 outbreak have caused increases in food insecurity in several countries, such as Greece and Italy, while rates are stable or declining in others, such as Finland and Sweden, indicating economic resilience and successful crisis management.

3.4. *Economic disparities and consumption patterns*

The analysis of per capita GDP in 2023 provides insight into economic disparities among EU member states that directly affect food access, affordability, and consumption patterns; as illustrated in Fig. 7, the brightly colored map highlights these differences across countries, emphasizing the uneven economic landscape within the EU.

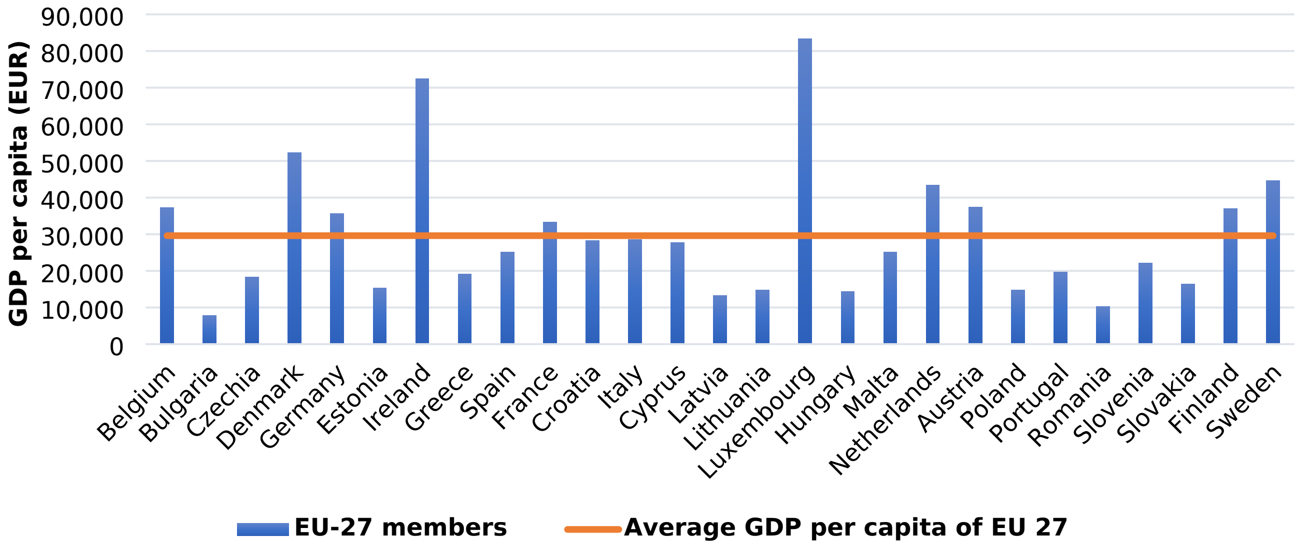

Fig. 7 GDP per capita in 2023 (EUR)

Source: own editing based on Eurostat [88]

Luxembourg is at the top of the chart with an exceptionally high per capita GDP value of over EUR 83,000, reflecting the country's economic superiority. Ireland also has a significant value, over EUR 72,000, indicating its thriving export-oriented economy. The figure clearly shows that the GDP values of Belgium, Germany, France, and the Netherlands are stable and above the EU average, showing their economic stability. In contrast, Bulgaria and Romania are at the bottom, with per capita GDP values around 9.000 EUR, reflecting their economic challenges. While the causes and effects of food waste are well understood, measuring and comparing how they appear in different EU regions indicate significant structural differences. For instance, per capita GDP data from 2023 indicate that wealthier countries like Germany, the Netherlands, and Denmark have relatively high levels of household food waste. This waste is mainly due to overconsumption and a lack of consumer awareness. On the contrary, countries such as Romania, Bulgaria, and Hungary, which have much lower-income levels, deal with higher postharvest losses. For instance, while Germany and the Netherlands combine high GDP per capita with strong national food waste strategies, in lower-income countries such as Romania or Bulgaria the absence of comparable policy instruments exacerbates postharvest losses.

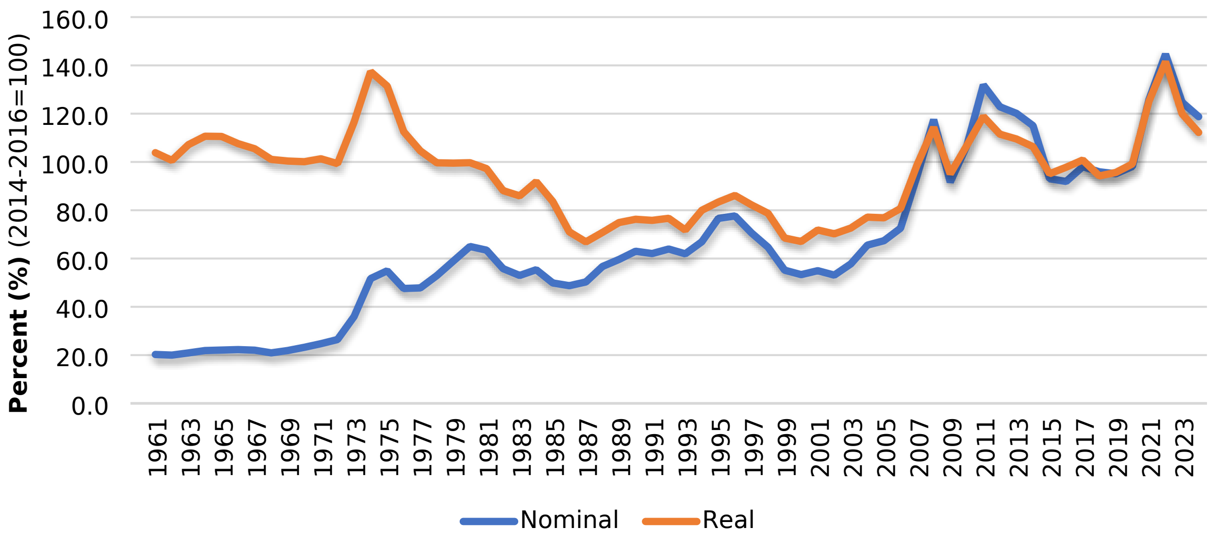

Fig 8. FAO food price index: nominal and real (1961-2023)

Source: Own editing based on FAO [89]

The line diagram shows the change in nominal and real values of the FAO Food Price Index between 1961 and 2023. Fig. 8 illustrates the continuous rise of nominal values (blue line), which can be observed especially from the end of the 1970s and the mid-2000s, associated with global economic trends and inflation. In contrast, the increase in real values (red dashed line) is more moderate, indicating actual price movements adjusted for inflation. In recent years, especially after 2020, both values have increased sharply, reflecting the impact of global economic crises and the COVID-19 epidemic. The clear display of years helps to review trends over time and quickly identify price spikes [89].

It is important to highlight that the pandemic affected all EU countries but with differing consumer responses regarding food availability, and waste varied widely depending on local conditions. In Italy, early lockdowns led to widespread panic buying and stockpiling, as in Hungary. Germany experienced a more moderate response, characterized by a surge in online grocery shopping and temporary supply chain bottlenecks. Nevertheless, household waste remained relatively stable due to strong food literacy and welfare support. In Hungary, stricter restrictions and income uncertainty led to more home cooking and careful food use, with reported reductions in waste among low-income households. In the Netherlands, behavioral shifts were mixed because of early overbuying. During the first COVID-19 lockdown, a nationwide survey of Greek consumers identified segment-specific, phase-dependent changes: early stockpiling by some groups increased waste risk, whereas later meal planning and at-home cooking reduced discards [90]. Complementing behavioural evidence, Greece produced an EU-framework national baseline for household food waste in 2021, reporting 86.5 ± 64.5 kg per capita and detailing composition by food category useful for post-COVID targeting of household interventions [91]. Lockdown reallocated consumption to households and raised weekly food purchases (≈ 13.8 kg/capita/week), with more home cooking-patterns which, when paired with planning, tend to lower plate waste [92]. At city level, Barcelona experienced a ≥ 25% reduction in tourist/commercial waste streams under restrictions, altering municipal waste composition and logistics [93]. These country patterns align with the evolving context of EU measurement and policy. Eurostat's latest estimate is 132 kg per capita for 2022, and the Commission's Farm-to-Fork initiative includes legally binding targets for food waste reduction and prevention [94]. These country-specific experiences show us that the effects of crises on food waste are not the same, even for those within the borders of the EU. Policymakers recognize that diversity is crucial when designing adaptive, crisis-sensitive food waste policies that are expected to be highly beneficial.

According to [95], the worldwide increase in food prices resulted in increased production, a process further strengthened by the growing demand for food. In an ambivalent way, while the production of food is expanding, in terms of the chance of access to food, increasingly large differences can be observed not only in developing countries but also in developed countries. Decision-makers should strive to improve equality of opportunity in terms of access to food. In other work, [96] analyzed the legal environment for the operation of food supply chains in the EU and found that the circular economy and waste law appear among the principles affecting food waste management. However, according to their study, the legislation in force at the time it was conducted did not significantly influence reductions in food waste [96]. To reduce wastage, economic policy incentives have become widespread, primarily based on the fact that with higher food prices, consumers become less willing to waste purchased food.

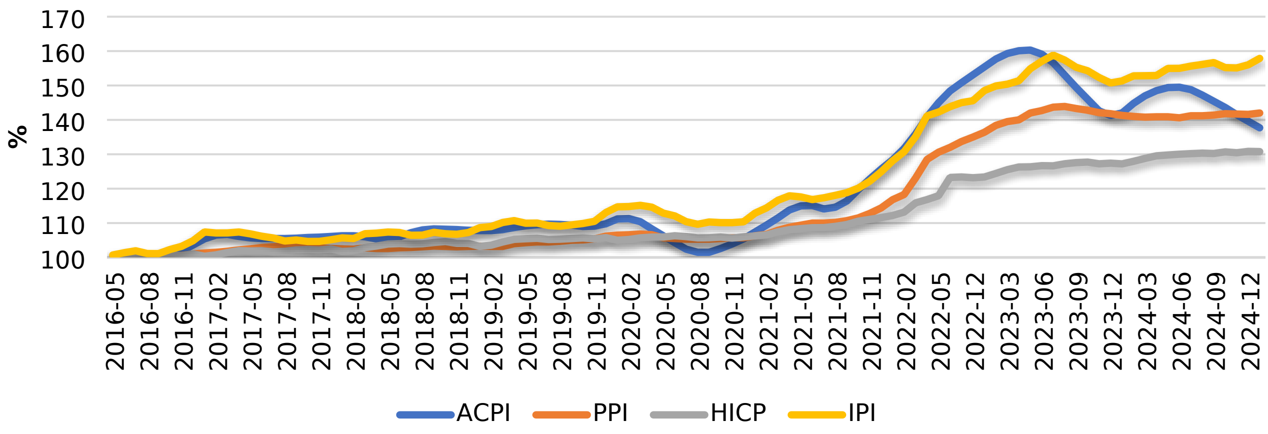

Fig. 9 Price trends along the food supply chain, 2005-2023

Source: Own editing based on Eurostat [97]

Fig. 9 tracks four price indices – agricultural consumer prices (ACPI), producer prices (PPI), HICP (consumer inflation), and industrial production prices (IPI) – from May 2016 to December 2024, using 2016 as the base (100%). From 2016 to 2020, all indices showed modest and stable growth, remaining under 115%, indicating a period of low inflation. This stability ends abruptly around early 2021, when all indices begin rising sharply, led by the ACPI and IPI. The spike peaks in mid-2022, with the ACPI surpassing 160%, reflecting severe food price inflation likely linked to post-COVID-19 disruptions, energy price shocks, and supply chain instability. The PPI also climbs significantly but lags slightly behind, suggesting a delayed cost pass-through to producers. Meanwhile, the HICP increases more slowly and steadily, peaking below 130%, indicating some insulation of consumer prices from upstream volatility, possibly due to policy measures or delayed transmission effects. By 2023–2024, the ACPI becomes volatile, while the other indices plateau or rise more gradually. This divergence highlights sector-specific inflation dynamics, with agriculture remaining particularly sensitive to external shocks. The ACPI shows the most extreme changes, while the HICP remains relatively stable, which can be useful for understanding economic trends and food price developments, as well as making future forecasts [97].

3.5. Typology of food waste policy interventions across supply chain stages and EU regions

To move beyond a basic summary and offer a deeper analysis, we developed a typology that links food waste measures to stages of the supply chain and regional vulnerabilities across the EU. This framework synthesizes insights from recent studies and policy evaluations while accounting for the economic diversity of EU member states.

Table 1 Policy–Economy–Food Security Nexus: context-sensitive intervention typology and evaluation metrics (EU)

Region type	**Macro-vulnerability**	**Supply-chain node**	**Primary policy lever**	**Expected mechanism**	**Indicative metrics (examples)**
Lower-income East (e.g., RO, BG)	*Postharvest loss & affordability risk*	*Postharvest & storage*	*CAP Pillar II (cold chain, storage, TA)*	*Reduced physical losses: greater availability; smoother farm-gate price variability*	*FLW at storage (%), cold-storage capacity per 1,000 t, volatility of wholesale prices*

Mixed urban–rural South (e.g., IT, ES)	*Retail mismatch; perishables*	*Distribution & retail*	*Donation incentives, VAT relief, label clarity*	*Increased redistribution; lower retail discards: improved access for vulnerable groups*	*Donated surplus (kg/cap), retail waste (kg/cap), share of "Best Before" relabelling*
High-income West/North (e.g., DE, NL)	*Household over-purchase; price spikes*	*Consumption*	*Awareness + date-label reform + e-commerce nudges*	*Fewer household discards; substitution toward shelf-stable planning: stability*	*Household FW (kg/cap), share of households checking labels, FI (moderate/severe) rate*

Source: Own editing based on this research, 2025

Table 1 presents a context-sensitive typology of political, economic and food security interventions in different EU regions. This illustrates that each part of the food supply chain faces different vulnerabilities and therefore requires targeted measures from CAP Pillar II post-harvest storage support in Eastern Europe to donation incentives in Southern Europe and awareness-raising or labelling reforms in Northern and Western Europe. This heterogeneity highlights the persistent gap between production-led instruments and sustainability-oriented objectives.

In response to the reviewer's concerns about the conceptual nature of Table 1, we have increased its robustness by linking each intervention category to the evidence base from our systematic review. Specifically, behavioral and educational campaigns were supported by 12 studies, regulatory/policy interventions by 28, redistribution/food bank programs by 3, economic instruments by 10, technological innovations by 15, and cold chain interventions by only 1 study. These comparative data highlight the uneven distribution of research attention and confirm that consumer and policy-level solutions dominate the literature. At the same time, structural interventions such as cold chain and redistribution remain underrepresented. Furthermore, our synthesis highlights the ongoing tension between the EU's sustainability aspirations – such as the Green Deal and the "farm to fork" strategy – and the CAP's historical focus on production intensity, especially in Eastern Europe. Several reviewed studies highlight that support structures for cereals and livestock continue to reinforce resource-intensive practices that counter the EU's 2030 50% food waste target. .

4 Discussion

Reducing food waste is vital for improving food security, particularly in the EU. This study demonstrates that enhancing the efficiency of the food supply chain can significantly increase the amount of available food, with substantial benefits both globally and regionally. Cutting food waste also reduces GHG emissions, as methane from decomposing food contributes significantly to global warming. These efforts align with the EU's Green Deal goals for 2050, aiming for carbon neutrality. Economically, reducing food waste lowers production and transport costs and boosts the efficiency of food distribution. Socially, it supports feeding people in need by providing food banks or other aid programs with consumable food. Consumer behavior significantly impacts food waste, especially in affluent regions where overconsumption and overbuying are common. Changing such behaviors can effectively reduce waste. The COVID-19 pandemic exposed the vulnerability of global supply chains and emphasized the importance of local food production and supply. When consumers increasingly turn to local producers, they create opportunities to strengthen local food systems, which could be crucial for future food security. Addressing food waste requires a comprehensive approach involving consumer behavioral changes, regulatory frameworks, and innovative technological solutions. Successful waste reduction contributes to sustainable food supply systems and environmental sustainability, aiding the fight against global warming.

Our proposals are set out below:

- **Food banks and redistribution**: Developing and supporting food bank systems is key to reducing food waste and improving food security. It is recommended that food close to its expiry date is directed to food banks, which will ensure its distribution to those in need. For example, effective personalization of hospital services and better management of the food system can increase food intake and reduce food waste among patients [98]. Another study presents options for the efficient management of food and kitchen waste and reviews the techniques and economic impact of producing value-added products from waste, such as biopolymers [99]. A critical assessment of biotechnological solutions should be undertaken to reduce food waste in the context of a circular economy.
- **Raising consumer awareness:** There is a need to raise consumer awareness of the problem of food waste. Education campaigns and community initiatives should encourage responsible purchasing and consumption habits and the use of leftover food. Raising consumer awareness is key to reducing food waste and improving food security. Education programs and community initiatives can make a significant contribution to the development of sustainable consumption habits and thereby reducing food waste [55]. The fight against food waste must actively involve the entire society, including consumers, to achieve long-term sustainable solutions [100-102].
- **Innovation and technological improvements:** Technological improvements in food supply chains, such as cold chain technologies and biotechnology, can effectively reduce food waste. The introduction and diffusion of such innovations should be supported. Various innovations have great potential to reduce and prevent food waste along the supply chain [103,104].
- **Regulatory measures:** Tightening the regulatory framework to reduce food waste, such as requiring food processors and retailers to minimize food waste, can help reduce waste [105,106].
- **Research and development:** Further research is needed to identify best practices and innovative solutions to reduce food waste. Australia generates a significant amount of food waste that can be recycled through various biorefinery processes [107]. Diversion of food waste from the solid waste stream to the wastewater stream is a promising method for source separation, collection, and treatment of food waste [108]. Converting food waste into biofuel offers significant environmental benefits by providing a sustainable energy source [109]. The use of food protein waste has a significant environmental impact and can be used to develop new materials and innovative technologies, such as biodegradable plastics, water purification, and renewable energy production [110].
- **Supporting local food production:** Supporting and developing local food production can reduce food supply chain vulnerability and contribute to increasing food security [111]. Local markets and producers should be encouraged to increase their resilience to global challenges [112].

We would also like to add some critical reflections on the EU Green Deal and Farm to Fork Strategy. While the European Green Deal and Farm to Fork Strategy set high goals for sustainable food systems, their implementation exposes important contradictions. Noticeable pressure can be seen between environmental targets, such as reducing food waste and pesticide use, and the ongoing CAP support for intensive production. This gap risks weakening sustainability efforts. Furthermore, differences in institutional capacity, especially in Eastern and Southern Europe, restrict the practical rollout of food waste solutions like redistribution infrastructure and cold chain systems. Enforcement measures are also weak and vary among member states. To address these gaps, we propose three actionable recommendations:

(1) Pilot food waste reduction incentives in high-waste regions,

(2) Link CAP funding to national food waste targets,

(3) Create regional support hubs to strengthen implementation capacity.

These suggestions aim to align EU ambitions with national realities and support more effective, regionally adapted food waste governance.

4.1. Limitations of the study

This study offers a qualitative overview of how food waste reduction relates to food security in the EU. While it provides valuable policy insights, we note some limitations. The work relies on secondary sources and does not include original empirical research, so findings are not fully statistically generalizable. We aimed to identify key patterns and intervention types, but data gaps, especially at the national level, limited deeper regional analysis. For example, differences between Western/Northern and Eastern/Southern EU countries could not always be fully explored. Still, the review lays a solid foundation for future, more data-driven research and policy development.

The implementation of EU-level research poses significant challenges, primarily due to the volume of financial and human resources required. Conducting a study at such a scale is extremely expensive, as not only is the need for data collection and processing equipment high, but also the coordination and maintenance of research groups operating in different parts of the country represent a significant organizational challenge. However, we hope that in the future, with the involvement of targeted grant opportunities, research capacity will gradually expand to the national level.

5 Conclusions

The review highlights the tensions between the Common Agricultural Policy (CAP), which continues to encourage production intensity, and the sustainability aspirations of the Farm to Fork Strategy and the European Green Deal. For example, several reviewed studies note that support structures for cereals and livestock in Eastern Europe have reinforced resource-intensive practices that conflict with EU-wide commitments to halve food waste by 2030. The research is based on a systematic literature review following the PRISMA framework combined with secondary data analysis from key databases such as FAO, Eurostat, and Our World in Data. From an initial pool of 472 articles, 74 were included in the final synthesis after applying strict inclusion criteria. The findings reveal that the largest share of food waste occurs at the consumer level, highlighting the need for behavioral change, technological innovation (e.g., cold chain systems), and supportive initiatives such as food banks and local food networks. The study emphasizes that reducing food waste is not only an environmental priority but also a socioeconomic imperative. It reduces GHG emissions, conserves natural resources, and enhances social equity. The article proposes several policy recommendations: expanding food bank systems, raising consumer awareness, strengthening regulatory frameworks, and promoting local food production. Ultimately, the research confirms that reducing food waste is essential for ensuring future food security, environmental sustainability, and socioeconomic resilience across Europe.

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Competing Interests The authors declare no competing interests.

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