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Potential Energy and Environmental Footprint Savings from Reducing Food Loss and Waste in Europe: A Scenario-Based Multiregional Input–Output Analysis

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ABSTRACT: Food loss and waste (FLW) contribute significantly to the global food system’s economic and environmental burdens, including substantial greenhouse gas (GHG) emissions, resource depletion, and waste management challenges. In alignment with the European Commission’s sustainability objectives and U.N. Sustainable Development Goal 12.3, this study explores the potential energy and environmental footprint savings achievable by halving FLW in Europe by 2030. Using a multiregional input–output model, we estimated the total global energy and environmental footprint savings across all stages of the food supply chain, considering industry-specific FLW rates and proportion weights. The findings reveal substantial environmental savings across Europe, with aggregate savings potentially reaching 51 Mt CO$_2$e (0.09 t CO$_2$e/p), 4,620 Mm$^3$ (8 m$^3$/p) of blue water, 106,446 km$^2$ (179 m$^2$/p) of cropland, 55,523 km$^2$ (93 m$^2$/p) of grassland, and 0.47 EJ (0.54 TJ/p) of energy. The greatest potential for savings was found in Western Europe, specifically in France, Germany, Belgium, and The Netherlands. However, countries with a lower per capita GDP, such as Greece, Croatia, Bulgaria, and Romania, also demonstrate significant per capita savings potential, indicating that wealth does not necessarily correlate with higher environmental savings. Agricultural production emerged as the stage with the highest footprint reduction potential for GHG and resource footprints across Europe, while the foodservice and institutional stages offer the greatest energy-saving potential. Geographical disparities underscore the need for region-specific policies. These results challenge the wealth-sustainability correlation and advocate for adaptable policies that transcend national wealth and accommodate regional disparities, underlining the pivotal roles of the agricultural production and consumption stages in footprint savings.

KEYWORDS: Europe, Food loss and waste, Food supply chain, Input–output analysis, Energy, Environmental footprints, EXIOBASE

1. INTRODUCTION

The European Union (EU) aims to reduce greenhouse gas emissions by 55% by 2030 toward climate neutrality by 2050. Food systems account for a third of Europe’s greenhouse gas (GHG) emissions and 28% of its land footprints. The agrifood system presents a viable opportunity to reduce the continent’s GHG emissions and meet regional and global climate goals while addressing pressing environmental challenges. The current global food loss and waste (FLW) levels are alarming, about one-third of all food produced is discarded annually. Recent studies suggest FLW, including farm-stage losses, could be as high as 40% of global food production, with consumption contributing significantly to most food waste along the supply chain. This wastage undermines global food security efforts, with nearly 690 million undernourished people worldwide. Economically, industrialized nations face almost double the costs of FLW compared to developing countries. FLW are responsible for 8–10% of global GHG emissions, a quarter of agricultural water use, and 23% of global cropland area. Evidently, addressing FLW throughout the supply chain is paramount for sustainable food systems. Aligned with the United Nation’s (U.N.) Sustainable Development Goal (SDG) 12.3.1 objective of halving food waste by 2030, the EU launched its Farm-to-Fork Strategy in 2020 and is committed to mitigating FLW, accentuated in the Circular Economy Action Plan. While standardized measurements for food waste have been agreed upon by EU countries, achieving the ambitious 2030 FLW target demands legislative commitment, thorough policy evaluations and revisions backed by reliable and timely data.

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necessary for well-informed policy initiatives and sustainable consumer behaviors.19

Most research on mitigating the food system’s climate and environmental impact through sustainable practices tend to lean towards dietary changes.20,21 However, recent attention has shifted to the potential environmental benefits of reducing FLW across national and international food supply chains.22,23 Such studies have deployed different techniques to evaluate the environmental impact of FLW, including bottom-up (e.g., coefficient method, life cycle assessment (LCA)) and top-down approaches (e.g., mass flow analysis (MFA)) and input–output analysis, or a combination of the two.24 While LCA approaches benefit from detailed product-specific data, their limitations include the subjective selection of system boundaries, leading to cutoffs from the full product system and truncation errors.24 Using FLW data and environmental intensities, coefficient methods offer a practical approach to assess the environmental impacts of food waste, yet they can be limited by boundary-setting biases and data uncertainties.24 While environmentally extended input–output (EE IO) methods offer comprehensive coverage of national to global supply chains, they tend to have comparatively low product, industry, and geographical granularity.25,26

Recent studies by Zhu et al.22 and Guo et al.24 provide a profound understanding of the global GHG emissions resulting from FLW and its management. Characterizing FLW from cradle-to-grave, Zhu and coauthors estimate 9.3 Gt carbon dioxide equivalent (CO₂e) in 2017 from global FLW, including emissions from food waste management systems. In contrast, Guo and colleagues identify regions with high FLW and related emissions through a hotspot analysis, positing that global farm-to-fork FLW resulted in 2.5 Gt CO₂e emissions in the same period. Like many studies, Zhu and colleagues primarily focus on GHG emissions, overlooking other relevant environmental impacts of FLW environmental impacts of FLW and excluding emissions linked to postharvest activities such as refrigeration and packaging. Also, Guo and coauthors suggest potential biases, uncertainties and data gaps when utilizing the FAO Food Balance Sheets database for modeling, emphasizing the need for data validation and uncertainty estimation. Both studies underscore the need for further research, especially national-level field surveys aimed at refining FLW estimates to improve the accuracy of GHG emission calculations related to FLW and to guide interventions addressing this global issue.

A growing body of research deploys environmentally extended multiregional input–output (EE MRIO) models with trade-linked national IO tables to assess the environmental footprints of food systems on national, regional27 and global scales.33 These models differentiate production-, consumption-, and trade-related environmental pressures of different food industries/products and food-related services throughout the country/regional global supply chains.34 Recent EE MRIO studies have examined the environmental impacts of FLW mitigation, each contributing distinct insights and inherent limitations.25,26,27,28 Read et al.25 estimate an 8–10% food-related energy and environmental footprint reduction in the U.S. food system from halving FLW but did not consider global trade footprints. Usubiaga et al.27 posit 2–7% food-related material and environmental footprint savings in the EU-28 from a 50% FLW reduction using U.K.-centric food waste rates for the broader EU context. Reutter et al.28 analyze Australia’s food consumption’s environmental and socio-economic impacts but neglected the impacts of imported food consumption and end-of-life waste treatment. Most prior studies did not incorporate rebound effects on food systems following FLW mitigation. Using a hybrid LCA and detailed EE MRIO analysis, Salemdee et al.26 estimated U.K. GHG emissions savings from food waste reduction but highlighted potential 60% savings reductions due to rebound effects. Their study, however, assumed an unchanged quality of life, mainly focused on GHGs, omitting impacts such as resource use. Together, these studies underscore the need for standardized methodologies, enhanced data precision, and region-specific research for broader applicable findings.

In the last three decades, the global food supply chain (FSC) has increasingly become a hotspot of environmental impacts from the agrifood system due to globalization and increasing global food trade.35,36 The increased reliance on imported food in European diets is associated with an increase in the displacement of environmental burdens on Europe’s regional and global trade partners.36 Feedback’s 2021 report,37 based on a meta-analysis of FLW studies, indicates a concerning trend in EU food security: annual FLW (154 Mt) exceeded agricultural imports (138 Mt) in 2021, resulting in an economic cost of €143 billion, contributing 6% of the EU’s total GHG emissions. Against this backdrop, this study attempts to answer the following questions:

1. What are Europe’s global food-related energy and environmental (specifically, climate, blue water, cropland, and grassland) footprints/pressures by the FSC stage and origin?

2. What potential energy and environmental footprint savings could result from reducing current FLW levels by 50% in Europe, in line with the current global and EU policies?

Leveraging the latest EXIOBASE global MRIO database (version 3.8.2), this study quantifies Europe’s consumption-based food-related energy and environmental footprints across the entire food supply chain (FSC), from agriculture production through processing to consumption. Using EXIOBASE’s 2018 global MRIO table, we estimate the pre-COVID-19 energy and environmental footprints as our baseline scenario. Our analysis encompasses 28 EU states, with the United Kingdom (an EU member in 2018), Switzerland, and Norway leading to a total of 30 European nations, while other European countries are grouped as the Rest of Europe (RoE) (Supporting Information (SI1), Table S1). Employing MRIO modeling, we circumvent system boundary delimitations challenges of LCA approaches while accounting for domestic and international trade-linked environmental pressures of European food consumption. Diverging from previous research that focused on specific European countries or regions,40–44 this study leverages an EE IO framework to provide a comprehensive analysis of the global FSC energy and environmental footprints of European food consumption and potential food-related footprint savings from a 50% FLW reduction in Europe.

Contrary to prior research,36,24,26 our study differentiates between domestic and imported FSC footprints and provides nuanced insights into trade-offs between energy and multiple environmental footprint indicators at a superior country detail for Europe. Our FLW modeling relies on more recent European FLW data, unlike the Usubiaga et al. study, which used 2007 U.K. data for the EU28 member states. To summarize, we present the baseline data (as of 2018) regarding
the energy and environmental footprints tied to European food consumption by origin and FSC stages and potential savings from halving FLW, presenting crucial policy insights to incentivize FSC optimization and global collaborations and increasing consumer awareness on the energy and environmental savings from halving FLW.

2. MATERIALS AND METHOD

Using MRIO analyses, we estimate Europe’s baseline FSC energy use, GHG, blue water, and land footprints. Counterfactually, we assessed the environmental footprint of halving Europe’s FLW by lowering industry and household food demand based on product and supply chain stage-specific FLW rates (see SI1, Table S5). The difference between the baseline and counterfactual footprints represents the potential energy and environmental savings from halving European FLW.

2.1. Multiregional Input–Output Modeling. Input–output (IO) analysis was originally conceived by Leontief to examine the implications of demand changes in the United States on value added and employment. The IO table derived from national supply-and-use tables (SUTs) forms the basis of the IO analysis. Input–output models provide insights into interindustry linkages and consumption patterns across broad product and industry groupings, though with less granular detail than LCA databases. Building on the System of Environmental-Economic Accounting (SEEA) framework, Environmentally Extended Input–Output (EE IO) models incorporate satellite accounts covering diverse socioeconomic and environmental indicators, enabling consumption-based environmental footprint analysis across multiple geospatial scales. Recent advancements in IO modeling have provided multiregional IO (MRIO) tables, which combine national IO tables with international trade data, and have been applied for multifaceted economic and supply chain analyses and environmental-consumption-based accounting. The MRIO model’s strength is its complete global economy coverage, addressing system boundary setting and truncation error limitations in LCAs. It consistently tracks the direct and indirect pressures of a nation’s consumption and the impact of internationally traded products/services throughout the supply chain. Various studies using EE MRIO analysis have examined both production- and consumption-based pressures/footprints from national to global scales, while others have explored footprint reduction potential through diverse socioeconomic and environmental policy interventions.

2.2. Data. 2.2.1. EXIOBASE Database. The primary data source for our EE MRIO analysis, the 2018 industry-by-industry EXIOBASE global MRIO database compiled under the industry technology assumption of identical production technologies across industries, implying industry production functions as weighted aggregates of primary and byproduct inputs based on respective outputs. EXIOBASE, developed from EU projects like EXIOPOL, CREEA, and DESIRE, connects the EE-SUTs of 44 countries and five Rest of the World (RoW) regions, resulting in a harmonized global MRIO table. It is applicable for estimating environmental pressures/footprints for 200 product groups and 163 industries, aligned with the European NACE classification scheme. Aligning with the SEEA, EXIOBASE attributes domestic production’s direct energy and environmental impacts to source products/industries, presenting an extensive satellite account with over 309 indicators covering energy, emissions, and resource use. Several studies have employed EXIOBASE to investigate the environmental pressures of global consumption and trade. While EXIOBASE provides MRIO tables spanning 1995–2022, most of its real data compilation concluded in 2011. Some MRIO data for subsequent years are derived from Nowcasting, an extrapolation technique utilizing partial trade records up to 2014 and macroeconomic data until 2016, thus enhancing EXIOBASE’s temporal span for in-depth longitudinal analysis.

2.3. Footprint Calculations. 2.3.1. Mapping the Food Supply Chains within the Input–Output Framework. Deploying the IO framework, our model captures the intermediate consumption stage—where food commodities are inputs for agrifood and nonfood industries—and the final consumption stage, where households purchase food for consumption. This enables detailed scrutiny of industry interdependencies and classification of EXIOBASE industries under distinct FSC stages (SI1, Table S3). The NACE classification provides a structured categorization of economic activities within the EU, ensuring clear demarcation of supply chains and facilitating the collection of extensive European and global economic data. Its hierarchical design captures the continuum of the agrifood chain, spanning from cultivation to commercial activities. In adherence to NACE and incorporating life cycle considerations within the IO framework, we identified 25 agrifood industries in EXIOBASE: associated with agriculture production and 11 associated with food processing (SI1, Table S3). Furthermore, 18 additional EXIOBASE industries were delineated, encompassing sectors such as hotels and public institutions where food is a secondary input or output. These were categorized under stages of food retail, foodservice, and institutional (Table S3).

Demand-pull model, the IO methodology posits a direct proportional relationship between industry inputs and outputs, upholding a fixed input structure and constant returns to scale. Consequently, we calculate p as the proportion of the economic value of agrifood product inputs in the aggregate economic value of all inputs per industry, derived using data from EXIOBASE’s transactions matrix (Z; see SI1, Supporting Information, section 2.3):

\[
\sum_{i=1}^{s=43} \frac{z_{ij}}{\sum_{j} z_{ij}}
\]

where “s” symbolizes the 43 EXIOBASE FSC-linked and represents the interindustry flow element of Z. Notably, for agriculture production such as cattle farming and wheat cultivation, p equals 1. In contrast, the retail, foodservice, and institutional industries providing industries like hotels, health and social work, and transport services, where food is a secondary output, have a p value less than 1 (see Supporting Information Two (SI2), Table S1.8).

2.3.2. Quantifying the Baseline Food Supply Chain Footprints. Leveraging EXIOBASE, our study examines Europe’s baseline FSC footprints across five key indicators: energy use (exajoules, Ej), greenhouse gas emissions (CO₂eq), blue water (Mm³), and land use (km²) (SI1, Supporting Information, section 2.2). Implementing the IO Leontief demand-pull model, the baseline footprints, Q_{fsc}, for 43 FSC-linked industries are derived as
Here, sk (k = 1···5) represents the energy and environmental intensities vector; I is the identity matrix; A is the direct input coefficient matrix; the Leontief inverse, (I − A)−1, accounts for direct and indirect input requirements; and yc fsc (yc fsc = ∑j Yij · pfsc) is the household expenditure on local and imported food products/services for the studied countries and RoE region. Of note, our consumption-based energy and environmental footprint accounts avoid double counting of pressures by attributing the direct energy and environmental impacts only to the final output and not the intermediate products. For the dimensions of variables in eq 2, refer to SI1, section 2.3. We present the cumulative footprint for Europe and its subregions, segmenting results by FSC stages (Tables S1 and S3).

 Furthermore, Q fsc is divided into domestic (Q fsc d) footprint of locally produced and consumed food products/services and imported (Q fsc m), embodied in food imports. Detailed explanations of the computational structure of EE IO analysis are addressed extensively elsewhere.34,47

2.3.3. Quantifying Potential Food Supply Chain Footprint Savings. To estimate the potential energy and environmental savings from halving Europe’s FLW, we compute the counterfactual footprints (Q fsc c) by modifying two variables from eq 2 (A and y c). We model a 50% FLW reduction across the FSC for industries (upstream) and households (downstream) based on product and stage FLW rates (SI1, Table S5) by reducing the industry food-related input requirements and household food demand to derive the counterfactual input coefficient matrix (A’, A ⇒ A’) and final demand. Counterfactual final demand is derived following Read et al.23 by reducing FLW rates (α) by 50% (r) for a food product/group:

\[
y_c' = yc fsc \left( 1 + p_{fsc} \left( \frac{1 - \alpha}{1 - \alpha(1 - r)} - 1 \right) \right)
\]

Here, FLW collectively represents “food loss” and “food waste”, as delineated in the FUSIONS72 framework. Food loss implies the reduction in mass of food, edible or otherwise, from harvest to retail stage, whereas food waste refers to reductions at the retail and consumer stages.73 Incorporating EU FLW rates from Caldeira et al.74 and Gustavsson et al.,73 we map these rates to EXIOBASE’s FSC industries (see SI1, section 2 and Tables S1, S4, and S5 for FLW data details). Caldeira and coauthors employed a top-down mass flow analysis to assess 2011 food waste in the EU, distinguishing waste from loss and supplying discrete values for various food categories and FSC stages. In contrast, Gustavsson and colleagues conducted a broad global assessment of FLW, utilizing FAO’s 2007 Food Balance Sheets to determine FLW across diverse food categories by FSC stage on a continental scale. When product-specific FLW rates are available for products grouped into a broad EXIOBASE industry, weighted averages represent aggregated EXIOBASE categories. While covering 46 European countries extensively, the UNEP Food Waste Index report6 does not provide product-specific FLW data or cover the agriculture production and food processing
3. RESULTS

3.1. Absolute and Per Capita Footprints. Figure 1 displays the baseline and counterfactual total FSC energy and environmental footprints of Europe and European subregions by food chain stages. In 2018, the baseline FSC footprints of Europe were as follows: GHG emissions (673 Mt CO$_2$e, 1.30 t CO$_2$e/p), blue water (69,901 Mm$^3$, 117 m$^3$/p), cropland (1,749,009 km$^2$, 2,936 m$^2$/p), grassland (873,696 km$^2$, 1,466 m$^2$/p), and energy (2.56 EJ, 4.36 TJ/p). For all indicators of Europe’s total FSC footprints, Western Europe held the dominant share followed by Southern Europe, respectively: GHG (40% and 24%), blue water (38% and 35%), cropland (36% and 25%), grassland (41% and 23%), and energy (42% and 26%). For all indicators, Northern Europe’s contributions exceeded those of Eastern Europe and the RoE (see SI1, Table S6).

Western Europe had the highest per capita total footprints for GHG (1.39 t CO$_2$e/p), cropland (3,260 m$^2$/p), and grassland (1,857 m$^2$/p) (see Figure S1). Conversely, Southern Europe is observed to have the highest per capita blue water footprint (178 m$^3$/p). Considering Luxembourg as an outlier due to its low population, it had the highest per capita total footprint for all indicators: GHG at 4.37 t CO$_2$e/p, blue water at 928 m$^3$/p, cropland at 18,041 m$^2$/p, grassland at 8,824 m$^2$/p, and energy at 16 TJ/p. Following Luxembourg, Denmark (1.88 t CO$_2$e/p) and Belgium (1.80 t CO$_2$e/p) had relatively high per capita GHG footprints, in contrast to Romania (0.38 t CO$_2$e/p) and Malta (0.27 t CO$_2$e/p), the bottom two countries. Spain (264 m$^3$/p) and Belgium (243 m$^3$/p) surpassed the regional and European per capita blue water footprint averages. Latvia, Belgium, and Denmark had

Figure 2 shows the baseline total FSC footprints at the country level based on their origin and stages along the FSC. Germany, France, and the United Kingdom constituted 16%, 15%, and 12% of Europe’s FSC GHG footprint, respectively. Spain (17%), France (15%), Germany (14%), and Italy (11%) accounted for more than half of the blue water footprint. The same group of countries dominated Europe’s cropland footprint, with France accounting for the highest share (17%), followed by Germany (13%) and Spain (11%). France (24%), the United Kingdom (13%), and Germany (12%) were the top 3 contributors to the grassland footprint. France accounted for over two-fifths of Europe’s energy footprint, followed by Greece (9%) and Italy (8%). Poland, The Netherlands, and Belgium contributed notably to Europe’s baseline FSC energy and environmental footprints.

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high cropland footprints per capita, while The Netherlands and Estonia had high grasslands per capita. Greece’s per capita energy footprint (12 TJ/p) was nearly triple the European average (see Figure S1).

### 3.2. Footprints by Origin and Stages

Europe’s domestic footprints comprised the highest share of its total FSC GHG (54%) and energy (53%) footprints (see Figure S2 and SI1, Table S6). However, imported footprints dominated the total FSC blue water (74%), cropland (64%), and grassland (69%). Across footprint indicators, the domestic footprint formed a high portion of Eastern (58–71%) and the Rest of Europe’s (52–70%) total footprints, except for blue water. In contrast, Western Europe had the highest share of imported footprints, ranging from 50% (GHG) to 93% (blue water). Bulgaria, the Czech Republic, Hungary, Romania, and Croatia are the only countries with domestic footprints contributing to more than half of the total footprint for four of the five footprint indicators under study. Northern Europe’s imported footprints had the largest share of the total footprint for all footprint indicators (SI1, Table S6). Fourteen of the 30 countries under study had imported footprints exceeding 50% of the total country-level footprints for all indicators, notably, Luxembourg, Austria, Belgium, The Netherlands, Ireland, Switzerland, Denmark, Sweden, Estonia, Cyprus, and Malta (see Figure 2).

Europe’s baseline total FSC GHG footprint was primarily driven by agriculture production (571 Mt CO₂e, 85%), followed by foodservice (46 Mt CO₂e, 7%) and processing (45 Mt CO₂e, 7%) (see Figure 1). Western and Southern Europe accounted for most of Europe’s FSC GHG footprints, especially in the agriculture production and foodservice stages. Germany, France, the United Kingdom, Italy, and Spain were the top five highest contributors to the GHG footprint across all stages. Agriculture also dominated Europe’s total blue water (98%, 68,614 Mm³), cropland (99.94%, 1,747,926 km²), and grassland footprints (>99%, 872,985 km²). Energy footprints showed a more balanced distribution across stages, although agriculture production (0.99 EJ, 39%) accounted for the largest share, followed by processing (0.77 EJ, 30%) and foodservice (0.61 EJ, 24%). Italy and France were observed to have the highest energy footprints in agriculture production, while Germany had the highest energy footprint at the processing stage. France dominated the energy footprint at the foodservice, retail, and institutional stages. The stage contributions to the total footprint contributions exhibited

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**Figure 3.** Energy and environmental footprint savings by origin: total (A) and per capita (B) for a modeled 50% reduction in Europe’s FLW under SDG 12.3. The data are based on eq 2. See Figures S10–S14 for domestic and imported footprint savings.
similar patterns for domestically produced and imported goods (see Figures S13−S14).

3.3. Absolute and Per Capita Total Footprint Savings. Figure 3 shows the total and per capita energy and environmental footprint savings from the projected 50% decrease in Europe’s FLW by origin. Europe could save up to 51 Mt CO\textsubscript{2}e (8% decrease relative to the baseline), 4,620 Mm\textsuperscript{3} of blue water (7% decrease), 106,446 km\textsuperscript{2} cropland (6% decrease), 55,523 km\textsuperscript{2} grassland (6% decrease), and 0.47 EJ of energy use (14% decrease) from a 50% decrease in its FLW (see Figure 1 and Table S8). The share of domestic footprint savings in total savings varied across indicators: energy use (70%), GHG (56%), cropland (35%), grassland (27%), and blue water (25%) (SI1, Table S8). Eastern Europe dominates domestic savings, especially cropland (57%) and grassland (58%), whereas Western Europe leads to energy savings (74%). Greece, Poland, and Croatia show the highest domestic footprint savings (Figure 3a). In contrast, Luxembourg, Belgium, and The Netherlands show the highest potential for reducing imported footprints. Western Europe had the largest share in total footprint savings for GHG (46%, 23 Mt CO\textsubscript{2}e), blue water (41%, 1,876 Mm\textsuperscript{3}), cropland (39%, 41,244 km\textsuperscript{2}), grassland (48%, 26,451 km\textsuperscript{2}), and energy use (55%, 0.26 EJ). France (15−43% of total savings), Germany (7−15%), and the United Kingdom (5−13%) showed the greatest potential for saving all footprint indicators, except for blue water savings, where Spain (17%) had the highest savings potential (Figure 3a).

On a per capita basis, Europe could save up to 0.09 t CO\textsubscript{2}e/p, 8 m\textsuperscript{3}/p of blue water, 179 m\textsuperscript{3}/p of cropland, 93 m\textsuperscript{2}/p of grassland, and 0.54 TJ/p energy use (see SI1, Table S8). Again, Western Europe had the highest per capita GHG and cropland, grassland, and energy footprint savings, except for blue water savings, where Southern Europe had the highest. Per capita GHG footprint savings are highest in Greece (0.31 t of CO\textsubscript{2}e/p), with Luxembourg (0.30 t of CO\textsubscript{2}e/p), and Belgium (0.26 t of CO\textsubscript{2}e/p), respectively. Luxembourg could achieve the highest per capita cropland (975 m\textsuperscript{2}/p) and grassland (498 m\textsuperscript{2}/p) savings, surpassing other potential big
savers such as Latvia, Belgium, and The Netherlands. Greece (4 TJ/p), France (1.76 TJ/p), and Luxembourg (1.67 TJ/p) had substantial per capita energy savings. Conversely, Malta, Romania, Slovakia, the United Kingdom, Germany, Sweden, and Denmark have lower European average potential savings across footprint indicators. Eastern Europe’s Bulgaria and Estonia could achieve above-average potential footprint savings for cropland (150 and 234 m²/p, respectively) and grassland (151 and 189 m²/p, respectively).

3.4. Footprint Savings by Origin and Stages. Figure 4 displays the contributions of the FSC stages to total savings and per-person savings by stage from a modeled 50% decrease in Europe’s FLW. Agriculture production offers the most substantial FSC footprint reductions: 65% for GHG (33 Mt CO₂e), and almost all of the savings for blue water (4,544 Mm³), cropland (106,338 km²), and grassland (55,368 km²) (see Figures 1 and 4a). In contrast, foodservice could yield the largest energy footprint reduction (50% or 0.18 EJ). At the agriculture production stage, potential GHG savings could be highest in France (19% or 6.3 Mt), Germany (14% or 4.6 Mt CO₂e), and the United Kingdom (11% or 3.8 Mt CO₂e), with Italy and Spain contributing 10% (3.4 Mt CO₂e) and 8% (2.6 Mt CO₂e), respectively. Other significant contributors include Poland, The Netherlands, Belgium, Austria, and Sweden. At the institutional stage, France could achieve the highest GHG savings (79% or 2.46 Mt CO₂e). Notable blue water savings were observed in Spain, France, Germany, and Italy, with potential contributions of 17% (770 Mm³), 15% (679 Mm³), 14% (669 Mm³), and 11% (487 Mm³), respectively. France, Germany, Spain, and the United Kingdom show the highest opportunities for cropland and grassland footprint savings. Substantial contributions were observed in Poland, The Netherlands, Austria, and Belgium.

Most of Europe’s energy footprint savings opportunities are observed at the foodservice (38%, 0.18 EJ) and institutional stages (31%, 0.14 EJ). France had the highest potential energy savings (0.20 EJ, 42% of the total), mainly in the institutional (0.11 EJ) and foodservice stages of the FSC (0.06 EJ), while Germany, Croatia, and Greece also showed significant opportunities for contributions at those stages. Europe’s per capita footprint savings across FSC stages revealed a significant contribution from the agriculture stage with a footprint of GHG, 0.06 t CO₂e/p; blue water, 8 m³/p; cropland, 178 m²/p; grassland, 93 m²/p; and energy, 0.127 TJ/p (see Figure 4b and S11, Table S10). Western Europe surfaced as the leading contributor to footprint savings across all FSC stages and indicators, followed closely by Southern Europe. While processing and retail stages contribute less to footprint savings across all regions, institutional and foodservice stages display varied patterns, with Western Europe having the largest energy savings (0.62 and 0.43 TJ/p, respectively). Luxembourg could significantly reduce per capita GHG (0.22 t CO₂e/p) and blue water footprints (58 m³/p) in the agricultural stage, followed by France (0.10 t CO₂e/p) and Spain (16 m³/p). Remarkable opportunities for cropland footprint reduction are observed in Luxembourg (974 m²/p) and Latvia (324 m²/p). Furthermore, the highest per capita energy footprint reductions could be achieved in Luxembourg’s agriculture production (0.55 TJ/p) and Greece’s foodservice (3.69 TJ/p).

4. DISCUSSION

4.1. Maximizing Farm-to-Fork Energy and Environmental Footprint Savings Potential. Our findings reveal that the agriculture production stage could account for up to 65% of the potential FSC GHG footprint reduction from halving FLW in Europe, along with almost all associated savings in land and water footprints (see Figures 1 and 4 and S11, Table S10). Primary agriculture production globally accounts for 1.2 Gt of annual on-farm food waste, equivalent to 15% of total food production, while in Europe, an estimated 20–25% of regional food produced is lost annually on farms.9,24,75 The results of our study underscore the global urgency to address environmental impacts from the food system, especially at the farm level. Despite the European Commission’s goal of a 55% reduction in agricultural greenhouse gas emissions by 2030, only 10% of food waste from primary production is currently addressed.76 We advocate for farm-level FLW mitigation integration within the EU farm-to-fork policy framework gate to achieve FLW reduction targets while urging Member States to voluntarily aim for a 50% reduction in pre- and postharvest waste by 2030.76 Promoting such a reduction requires strategic resource allocation, stakeholder collaboration, adoption of new technologies, and optimized farm practices while acknowledging barriers such as farmer awareness, financial constraints, and resistance to change.77,78 Our results highlight significant energy footprint reductions within Europe’s FSC, primarily achievable at retail, foodservice, and institutional stages, potentially contributing to 68% of the total savings (see Figure 1). Policy measures should incentivize energy-efficient practices in these stages through mandates for high-efficiency infrastructure, data-driven waste analytics, portion size customization, obligatory surplus food donation, strategic menu planning, behavioral changes toward waste minimization, and sustainability-oriented staff training.13,79,80

4.2. Reducing Footprints: Trade, Food Policies, and Environmental Sustainability. Empirical studies indicate that carbon leakage and transboundary environmental degradation linked to increasing global food trade disproportionately mitigate environmental burdens in affluent nations while intensifying them in emergent and less wealthy countries.36,81 Our results indicate that Europe’s increasing reliance on imported food products contributes to a significant portion of the continent’s FSC footprints but varies across countries (see Figure 2a). Our findings indicate that FLW reduction in Europe could significantly save the energy and environmental footprints embodied in European food imports, particularly for blue water and land use (see Figure 2a and S11, Table S6). Western and Northern Europe have the highest shares of imported footprint savings in total footprints across most indicators (S11, Table S6). Across most footprint indicators, France, Germany, Belgium, and The Netherlands had the highest savings potential in absolute FSC footprints embodied in food imports (see Figure 2a). Drawing on these results, we advocate for the implementation of strategic policies to enhance agricultural trade integration, aimed at reducing inefficiencies in global food systems by incentivizing sustainable production practices and conducting awareness campaigns on sustainable consumption, standardized and effective ecolabeling, improved supply chain management, and international cooperation to enhance resource efficiency.72,82,83

4.3. Disparities in Food Waste and Potential Footprint Savings. Earlier studies have suggested mixed results for the correlation between per capita income and food waste, implying the necessity for region-specific waste-reduction
strategies. Eurostat data reveal variances in per capita total food waste across EU countries, with high-GDP countries like Belgium (0.40 t) wasting more food than lower-GDP counterparts like Bulgaria (0.09 t), but exceptions like Germany and France challenge this trend (Figure S17). Despite having high GDP per capita, both countries have per capita food waste levels close to the EU average (0.13 t). The correlation between per capita food waste and footprint savings from a 50% reduction in FLW is nonlinear across footprint indicators (see Figure 5). Our results emphasize the complex relationship between wealth−food waste and environmental benefits from FLW mitigation, highlighting the importance of considering tailored FLW mitigation strategies and rebound effects across Europe.

For instance, Luxembourg displays significant savings potential despite its relatively moderate food waste levels (Figures 4 and S17). France has the highest potential for GHG and energy savings despite lower per capita food waste, while Cyprus shows only moderate savings across indicators despite high per capita food waste (Figure 4). According to Lopez Barrera and Hertel, food waste increases initially with income as consumption rises, then decreases as consumer awareness of food value improves, but increases again as lifestyle changes with further income growth. These results highlight the need for country-specific, tailored policies to reduce FLW and its environmental impact in Europe, aligned with global FLW reduction objectives.

4.4. Limitations of Study. Global MRIO databases like EXIOBASE have inherent constraints due to uncertainties in IO source data, modeling assumptions, and computational intricacies related to forecasting and balancing procedures used in MRIO table construction. Their static nature and often low product/industry granularity hinder their efficacy in intertemporal scenario modeling encompassing changes in economic variables, technological advancements, and consumer behavioral patterns due to policy interventions. Omissions from our analysis, partly attributable to EXIOBASE data limitations, include indirect land-use change emissions and direct household impacts, potentially leading to an underestimation of FSC footprints (see Supporting Information, section 4 for further details on IO limitations). The low-resolution and outdated FLW data, combined with assumptions like uniform FLW rates, could affect the accuracy of footprint savings estimates. Addressing MRIO data gaps and refining IO methodologies are pivotal for improving their applicability to policies supporting sustainable food systems. Country-level studies focusing on providing reliable food product- and stage-specific FLW rates throughout product life cycles warrant prioritization in future research. A recent study suggests that consumption rebounds could offset 53−71% of the environmental and food security benefits from a potential 1.3 Gt global FLW reduction. Further research is needed to investigate the rebound effects on footprint savings from FLW mitigation in Europe.

ASSOCIATED CONTENT

Data Availability Statement
Computation scripts and supplementary data are available upon request.

Figure 5. Per capita food supply chain energy and environmental footprint savings correlation with 2018 country food waste, derived from authors’ analysis and Eurostat. See Figures S17−S21 for stage-specific data and Figures S15−S16 for food waste’s relation to per capita GDP.
Supporting Information
The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.3c00158.

S1: Details on EXIOBASE country and industry classifications, food loss and waste rates and data sources, environmental satellite accounts, footprint calculation explanations, additional results, uncertainty and data limitations, and cited references (PDF)

S2: Data for the analysis, including food loss and waste rates data compiled from the literature, concordance matrices linking food industries and supply chain stages, European country food waste data, and cited references (XLSX)

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Notes
The authors declare no competing financial interest.

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