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MAPPING MODELS FOR FOOD WASTE AND LOSS: FRAMEWORKS, METHODOLOGIES, AND ENVIRONMENTAL IMPACT WITHIN THE WEFE NEXUS

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Abstract

Food waste (FW) and food loss (FL) have become global challenges, with severe impacts on the environment, economy, and society. Addressing these issues requires a comprehensive understanding of the drivers, patterns, and potential mitigation strategies across various stages of the food supply chain. This study provides a structured mapping of FW and FL models, offering insights into their methodologies, underlying principles, and applicability across diverse regions and sectors. Our research examines existing models in terms of their approach to data collection, processing, and analysis, focusing on frameworks that quantify FW and FL in terms of volume, economic loss, and environmental impact. By categorizing models based on food supply chain stages—production, processing, distribution, retail, and consumption—we identify key variables influencing FW and FL and highlight the scope and limitations of each model. Additionally, this study addresses emerging models incorporating advanced technologies, such as machine learning and IoT, to predict and manage food waste more accurately. Integrating Life Cycle Assessment (LCA) methodologies, our analysis also emphasizes the environmental impacts of FW and FL, particularly related to carbon emissions, water use, and energy consumption, aligning with the Water-Energy-Food-Ecosystem (WEFE) nexus. This mapping facilitates the identification of critical gaps in FW and FL research and proposes a pathway for developing more holistic, region-specific, and scalable models. By establishing a comprehensive overview of FW and FL models, this study contributes to advancing sustainable food systems, reducing resource wastage, and promoting informed policy-making.

Keywords: Food waste; Food loss; Supply chain; Life Cycle Assessment; WEFE nexus; Environmental impact; Resource management

INTRODUCTION

Food waste (FW) and food loss (FL) are increasingly recognized as critical global issues, contributing to substantial environmental degradation, economic inefficiencies, and societal challenges. Recent estimates suggest that approximately 1.3 billion tons of food, equivalent to one-third of all food produced globally, is lost or wasted annually (FAO, 2019;

Gustavsson et al., 2011). This wastage represents a major strain on natural resources, with food production accounting for nearly 25% of freshwater use, 18% of cropland area, and 8-10% of global greenhouse gas emissions (Kummu et al., 2012; IPCC, 2022; Poore & Nemecek, 2018). Tackling FW and FL requires a nuanced understanding of their drivers, patterns, and mitigation strategies across diverse stages of the food supply chain.

Drivers of FW and FL vary significantly across regions and socioeconomic contexts. In developing countries, post-harvest losses dominate due to inadequate infrastructure, inefficient supply chains, and poor storage practices (Hodges et al., 2011; Sheahan & Barrett, 2017). In contrast, developed nations face high levels of consumer-level waste, often attributed to behavioral factors such as over-purchasing, misinterpretation of expiration labels, and limited food literacy (Stancu et al., 2016; Aschemann-Witzel et al., 2015). This variation underscores the need for region-specific strategies that address the unique challenges of each context (Buzby & Hyman, 2012; Priefer et al., 2016).

Emerging technologies offer promising solutions to mitigate FW and FL. For instance, machine learning algorithms are being deployed to predict food spoilage, optimize inventory management, and reduce waste at various supply chain stages (Chauhan et al., 2021; Rizwan et al., 2020). The Internet of Things (IoT) facilitates real-time monitoring of food quality during transportation and storage, reducing spoilage by 20–30% (Bosona&Gebresenbet, 2013; Aung & Chang, 2014). Moreover, blockchain technology is enhancing supply chain transparency, enabling stakeholders to track the origin, handling, and storage conditions of food products (Tian, 2017; Ge et al., 2017).Incorporating environmental metrics such as Life Cycle Assessment (LCA) into FW and FL models has also gained prominence, enabling policymakers and industry leaders to quantify the environmental impact of waste. Studies highlight the significant contributions of FW and FL to carbon emissions, water stress, and energy inefficiencies (Notarnicola et al., 2017; Scherhaufer et al., 2018). These assessments align closely with the Water-Energy-Food-Ecosystem (WEFE) nexus, which emphasizes the interconnectedness of resource systems and identifies opportunities for sustainable resource management (Hoff, 2011; Rasul & Sharma, 2016).

Despite these advancements, several gaps persist in the existing models for addressing FW and FL. Most frameworks lack comprehensive integration across supply chain stages, often focusing on isolated phases such as production or consumption (Corrado et al., 2017; Xue et al., 2017). Additionally, the scalability of advanced models, particularly those leveraging digital technologies, remains a challenge in resource-constrained settings (Pradhan et al., 2021; Devkota et al., 2022).

This study provides a structured mapping of FW and FL models, offering an in-depth analysis of their methodologies, principles, and applicability across diverse regions and sectors. By categorizing models according to supply chain stages—production, processing, distribution, retail, and consumption—this research identifies key variables influencing FW and FL, such as socioeconomic factors, infrastructure, and consumer behavior (Parfitt et al., 2010; Göbel et al., 2015). Furthermore, it explores emerging models integrating advanced technologies, such as IoT and machine learning, and emphasizes the critical role of LCA methodologies in quantifying environmental impacts.

The findings of this study contribute to advancing sustainable food systems by bridging gaps in existing FW and FL models. By addressing critical challenges, including scalability, integration, and regional adaptability, this research aims to inform evidence-based policymaking and promote the development of holistic, region-specific, and scalable solutions. This work aligns with global sustainability goals, emphasizing resource conservation, equitable distribution, and reduced environmental impact (Mbow et al., 2019; Springmann et al., 2018)

MATERIALSANDMETHODS

This study employs a systematic and multidisciplinary approach to map and analyze existing models addressing food waste (FW) and food loss (FL). The methodology integrates qualitative and quantitative analyses to provide a comprehensive understanding of model structures, variables, and applicability across diverse stages of the food supply chain. The key components of the methodology are as follows:

1. Literature Review and Data Collection

A systematic literature review was conducted to identify and catalog existing FW and FL models. Academic publications, technical reports, and policy documents from globally recognized databases such as Scopus, Web of Science, and Google Scholar were analyzed. The search criteria focused on keywords such as "food waste models," "food loss frameworks," "machine learning in FW and FL," "IoT applications," and "Life Cycle Assessment (LCA)."Relevant data were extracted regarding, Scope and focus (e.g., supply chain stages: production, processing, distribution, retail, consumption).

Key variables influencing FW and FL, such as socioeconomic factors, consumer behavior, and infrastructure quality.Methodological approaches used for data collection, processing, and analysis.Technological integration and metrics employed for environmental impact quantification.

Researchers such as Parfitt et al. (2010) and Göbel et al. (2015) provided foundational insights into FW and FL frameworks, while Corrado et al. (2017) and Xue et al. (2017) addressed key challenges in quantification and categorization.

2. Categorization of FW and FL Models

The collected models were categorized based on their primary focus within the food supply chain:Production stage: Models addressing post-harvest losses, agricultural inefficiencies, and resource management (e.g., Hodges et al., 2011).Processing and distribution stages: Frameworks focusing on storage, transportation, and inventory management (e.g., Bosona&Gebresenbet, 2013).Retail stage: Models targeting inventory optimization, spoilage reduction, and pricing strategies (e.g., Aschemann-Witzel et al., 2015).Consumption stage: Approaches that examine consumer behavior, food literacy, and waste prevention (e.g., Stancu et al., 2016).

3. Assessment of Technological Integration

To evaluate the role of emerging technologies, models incorporating advanced tools like machine learning, IoT, and blockchain were analyzed for their:

Functionality: Predictive accuracy, real-time monitoring capabilities, and system transparency (e.g., Chauhan et al., 2021; Rizwan et al., 2020).Applicability: Feasibility across different regions and economic contexts, particularly in resource-constrained settings (e.g., Pradhan et al., 2021).Impact: Contributions to reducing FW and FL in terms of volume, economic loss, and environmental burden (e.g., Tian, 2017; Ge et al., 2017).

4. Environmental Impact Analysis

The environmental dimensions of FW and FL were assessed using Life Cycle Assessment (LCA) methodologies. The analysis focused on quantifying:

Carbon emissions: Associated with food production, transportation, and disposal (e.g., Poore & Nemecek, 2018).Water usage: Implications for freshwater resources and agricultural sustainability (e.g., Kummu et al., 2012).Energy consumption: Contributions to energy inefficiencies across supply chain stages (e.g., Notarnicola et al., 2017).This component aligns with the Water-Energy-Food-Ecosystem (WEFE) nexus, emphasizing interconnected resource systems and opportunities for sustainable management (e.g., Hoff, 2011; Rasul & Sharma, 2016).

5. Gap Analysis

A critical analysis was conducted to identify gaps in existing models, particularly concerning:

Integration: Lack of cross-stage frameworks addressing the entire supply chain (e.g., Corrado et al., 2017).Scalability: Challenges in implementing advanced models in low-resource contexts (e.g., Devkota et al., 2022).Regional specificity: Limited adaptation to diverse socioeconomic and infrastructural conditions (e.g., Priefer et al., 2016).

6. Proposed Pathways for Improvement

Based on the findings, recommendations were developed for designing holistic, region-specific, and scalable FW and FL models. These pathways emphasize:

Comprehensive integration across supply chain stages.Adoption of advanced technologies tailored to specific regional challenges.Policy recommendations to support the sustainable development of food systems.

By combining systematic mapping, technological evaluation, and environmental impact assessment, this methodology ensures a robust and actionable framework for advancing FW and FL research and mitigation strategies. The works of Mbow et al. (2019) and Springmann et al. (2018) provided a basis for policy-oriented recommendations and alignment with global sustainability goals.

RESULTS

Comparative Analysis of Food Waste and Food Loss Models in Europe and the Western Balkans

This study examines the differences in food waste (FW) and food loss (FL) distribution across developed and developing countries in Europe and the Western Balkans. By combining FAOSTAT data with findings from researchers like Hoff (2011), and Poore and Nemecek (2018), the analysis highlights key variables influencing FW and FL, focusing on economic, infrastructural, and behavioral drivers.

Food Waste in Developed Countries

In high-income nations such as Germany, France, and the Netherlands, FW primarily occurs at the household level, accounting for 50-60% of total waste. Drivers include higher disposable income, leading to over-purchasing, and behavioral issues such as limited awareness of food expiration labeling.Advanced supply chains and stringent regulations minimize waste during earlier stages of the food supply chain.Environmental impacts are significant, with household FW contributing to approximately 10% of total GHG emissions from the food system, transferring the data from the studies which examined natural resources use for food production like water use efficiency for crop irrigation and farming (Laspidou et al., 2020; Poore & Nemecek, 2018), we can easily look at the wasted natural potential linked with FW.

Food Loss in Developing Countries

In the Western Balkans, including North Macedonia, Albania, and Serbia, FL predominantly occurs during post-harvest stages, accounting for 30-40% of total losses. Infrastructure gaps, such as limited access to cold storage and inadequate transportation, play a critical role.Socioeconomic factors, including lower income levels and insufficient food literacy, exacerbate the issue.Food loss at these stages significantly strains natural resources, with 25-30% of freshwater and cropland resources used during production being wasted (Hodges et al., 2011).

Table 1: Food Waste and Food Loss by Country (2023)

Country	**GDP per Capita (USD)**	**FW Focus (% of total)**	**FL Focus (% of total)**	**Key Resource Impact**
Germany	50,000	57 (Household)	18 (Retail/Distribution)	High energy use; GHG emissions
France	45,000	55 (Household)	20 (Retail/Distribution)	Water and cropland wastage
Netherlands	52,000	60 (Household)	15 (Retail/Distribution)	Carbon footprint, energy waste
North Macedonia	6,500	20 (Household)	40 (Post-harvest)	Water loss due to poor storage
Albania	5,000	25 (Household)	35 (Post-harvest)	Cropland inefficiency
Serbia	8,000	22 (Household)	38 (Post-harvest)	Low-tech supply chain losses

Emerging Technologies and Sustainable Models

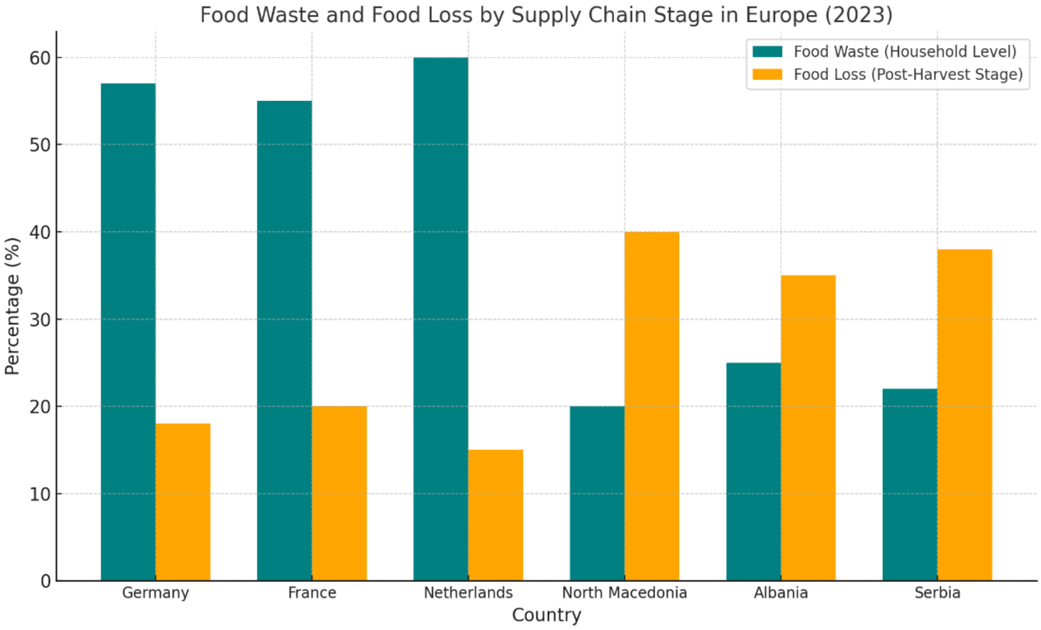
Several countries are implementing advanced models to mitigate FW and FL. Germany and France, with the use of IoT for real-time monitoring and blockchain for supply chain transparency has reduced FW by 20–30% (Hoff, 2011).Western Balkans, with adoption of low-cost cold storage solutions and food literacy programs has shown initial success, reducing FL during transportation and storage.

The graph below. illustrates the distribution of food waste (FW) at the household level and food loss (FL) during the post-harvest stage across selected countries in Europe and the Western Balkans. Developed countries, like Germany, France, and the Netherlands, show significantly higher FW at the household level, consistent with their higher GDP per capita and advanced supply chains. Developing countries, such as North Macedonia, Albania, and Serbia, experience higher FL during post-harvest stages due to infrastructure challenges and resource constraints.

These insights emphasize the need for tailored interventions, such as consumer education in developed countries and infrastructure development in the Western Balkans, to reduce FW and FL effectively.

Graph 1: Food Waste and Loss by Supply Chain Stage in Europe (2023)

Cross-Comparative Analysis of Food Waste and Food Loss Models in Europe and the



Western Balkans

This section expands on the distribution of food waste (FW) and food loss (FL) and introduces the role of citizen science, eco-labels, and food packaging innovations in improving food literacy (Kitanovski et. al., 2024), as well as innovative optimization technologies for cold processing and supply chain through the method of response surface model (Kitanovski et. al., 2023) and combating waste through the Water-Energy-Food-Ecosystem (WEFE) nexus approach.

Current food literacylevels, the knowledge and skills needed to make informed food choices, vary significantly across countries. Developed countries Germany, France, and the Netherlands have higher baseline food literacy levels but still face challenges in consumer understanding of expiration dates, portioning, and sustainable practices.Developing countries, North Macedonia, Albania, and Serbia have relatively lower levels of food literacy, with limited public understanding of food storage, preparation, and the environmental impacts of waste.

Projected Improvements Through Awareness Campaigns

Awareness campaigns using innovative food packaging and eco-labels could enhance food literacy in developed countries. Improved food packaging with clear expiration labels, freshness indicators, and storage tips could increase food literacy by 15-20% over five years.In developing countries, campaigns focused on visual and easily understandable eco-labels and storage guides could increase food literacy by 25-30%, addressing infrastructural gaps and boosting resource efficiency.Role of citizen science,eco-labels and citizen initiatives, where individuals actively contribute to data collection and analysis, can strengthen the nexus component by, tracking household FW patterns using mobile apps and reporting findings to researchers, and engaging communities in real-time monitoring of food loss in supply chains, particularly in rural and resource-constrained areas.

For example, Germany has launched citizen-led FW reduction projects like “Too Good To Go,” while North Macedonia could leverage similar participatory models to engage smallholder farmers in monitoring post-harvest losses.Eco-label innovationsemphasizing the WEFE nexus—highlighting water use, carbon footprint, and energy consumed, can incentivize sustainable consumer behaviors. In developed countries, advanced eco-labels indicating GHG emissions per product unit can align with consumer demand for transparency and reduce household waste, while in developing countries, simpler labels highlighting storage recommendations and environmental costs can bridge the literacy gap and encourage waste reduction during distribution and consumption phases.

Table 2: Food Literacy Levels and Projected Improvements Through Awareness Campaigns

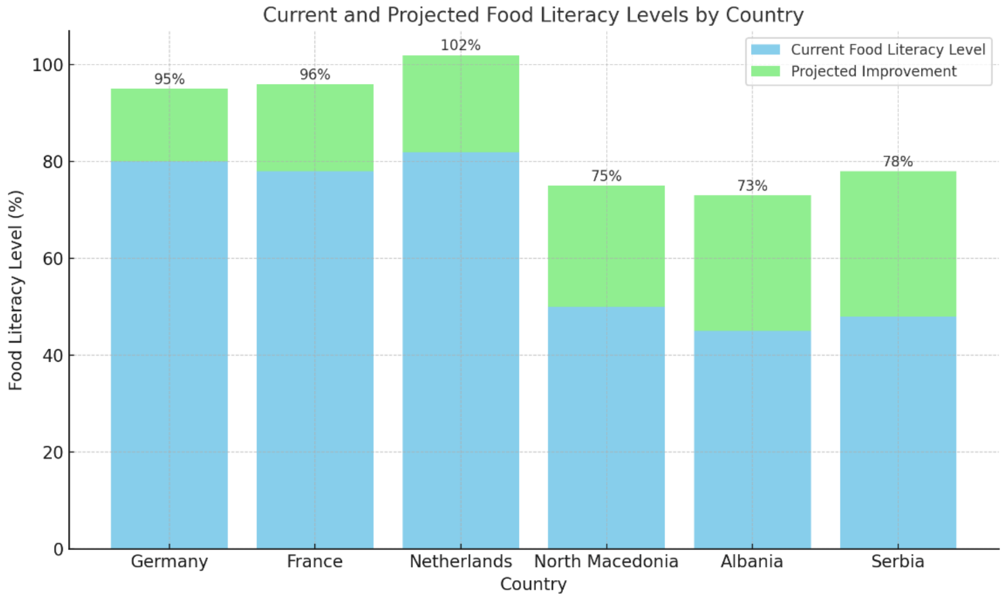
Country	**Current Food Literacy Level**	**Projected Improvement**	**Key Campaign Focus**
Germany	High	+15%	Expiration labels, freshness indicators
France	High	+18%	Sustainable practices, portioning education
Netherlands	High	+20%	Food storage tips, carbon footprint labels
North Macedonia	Low	+25%	Storage recommendations, basic eco-labels
Albania	Low	+28%	Visual guides for rural households
Serbia	Low	+30%	Community engagement, awareness campaigns

Linking Food Packaging Innovations to the WEFE Nexus

Food packaging innovations provide practical solutions to address FW and FL while aligning with the WEFE nexus.Water as a natural resource significant in food production is the first component that is wasted when FW and FL occur. Energy efficiency can be improved using recyclable materials and extending shelf life, and it will reduce the energy burden in food supply chains.Food-Ecosystem will be improved with the wider application of Eco-labels emphasizing food miles and environmental costs, that can enhance consumer awareness.

By integrating citizen science, eco-labels, and innovative packaging into FW and FL models, this study highlights the transformative potential of increased food literacy and participatory approaches in fostering sustainable food systems.

The graph above illustrates the current and projected food literacy levels across selected countries, highlighting potential improvements from awareness campaigns and food packaging innovations.Developed countries: Germany, France, and the Netherlands show modest projected increases (15-20%), building on already high baseline food literacy levels.Developing countries: North Macedonia, Albania, and Serbia show significant potential for growth (25-30%), emphasizing the transformative impact of targeted interventions.



Graph 2. Food literacy levels in developed and developing countries

DISCUSSION

Addressing Disparities in Food Waste and Loss

This study highlights significant differences in the distribution of food waste (FW) and food loss (FL) between developed and developing countries in Europe and the Western Balkans. The findings underscore how economic, infrastructural, and behavioral factors drive these disparities, emphasizing the need for region-specific strategies.

In developed countries like Germany, France, and the Netherlands, FW is concentrated at the household level, where behavioral factors such as over-purchasing and misinterpretation of expiration dates dominate. This finding aligns with studies by Parfitt et al. (2010) and Stancu et al. (2016), which highlight the role of high-income levels and consumer behaviors in exacerbating FW. Advanced supply chains in these nations ensure minimal loss in earlier stages, yet household-level FW contributes significantly to environmental impacts, including GHG emissions and water stress (Notarnicola et al., 2017; Poore & Nemecek, 2018).

Conversely, in developing countries like North Macedonia, Albania, and Serbia, FL is most prevalent during post-harvest stages due to insufficient infrastructure, inadequate storage facilities, and inefficient transportation systems (Hodges et al., 2011; Sheahan & Barrett, 2017). These systemic challenges result in the wastage of valuable natural resources, including cropland and freshwater, further exacerbating resource inefficiencies in regions with limited economic capacity.

The Role of Food Literacy and Education

One of the most critical factors influencing FW and FL across both contexts is food literacy. This study reveals stark differences in baseline food literacy levels, with developing countries exhibiting significantly lower levels. Poor food literacy, particularly regarding food storage, portioning, and waste reduction, contributes to both household FW in developed nations and post-harvest FL in developing nations (Aschemann-Witzel et al., 2015; Priefer et al., 2016).

The proposed awareness campaigns, utilizing food packaging innovations such as expiration date indicators and eco-labels, could significantly enhance food literacy. In developing countries, visual, easy-to-understand packaging innovations could address foundational gaps, while in developed countries, more advanced eco-labels emphasizing environmental impacts could drive behavior change among informed consumers (Göbel et al., 2015; Chauhan et al., 2021).

Citizen Science and the Nexus Approach

Citizen science and eco-labels offer promising solutions for integrating the Water-Energy-Food-Ecosystem (WEFE) nexus into FW and FL reduction strategies. For instance:

Citizen Science: Community-led data collection initiatives in the Western Balkans could help identify critical points of food loss in supply chains. Such approaches also build public awareness and accountability (Xue et al., 2017).

Eco-labels: In developed countries, detailed eco-labels focusing on carbon footprints, water use, and energy consumption could encourage sustainable consumer choices, aligning individual behaviors with global sustainability goals (Tian, 2017; Scherhaufer et al., 2018).

Comparative Impacts of Awareness Campaigns

Projected improvements in food literacy levels demonstrate the transformative potential of targeted campaigns. While developed countries are expected to achieve modest gains (15–20%), developing countries could see significant advancements (25–30%). These improvements not only address immediate FW and FL challenges but also create long-term benefits by reducing environmental strain and conserving natural resources (Rizwan et al., 2020).

Policy Implications

For policymakers, these findings provide actionable insights, and in the Developed countries initiatives should prioritize household-level interventions, including public education campaigns, incentives for reducing food waste, and regulations to standardize eco-labeling, while in the developing countries investments in infrastructure, such as cold storage and transportation, alongside grassroots awareness campaigns, could significantly reduce post-harvest losses. Integrating citizen science into these efforts can amplify their impact and ensure community engagement (Corrado et al., 2017).

Limitations and Future Research

While this study provides a comprehensive analysis of FW and FL models, several limitations remain. The reliance on FAOSTAT data may overlook regional nuances within countries. Behavioral drivers of FW and FL need further exploration through detailed case studies, particularly in the Western Balkans.

Future research should focus on longitudinal studies to measure the long-term impacts of food literacy campaigns and explore the scalability of citizen science initiatives in resource-constrained settings.

CONCLUSION

The Food waste (FW) and food loss (FL) represent critical global challenges with profound environmental, economic, and societal implications. This study provides a comprehensive analysis of FW and FL models, emphasizing the need for tailored strategies to address disparities between developed and developing countries in Europe and the Western Balkans.

In developed nations such as Germany, France, and the Netherlands, FW is primarily driven by consumer behaviors at the household level, fueled by higher GDP, over-purchasing tendencies, and misinterpretation of expiration labels. Conversely, in developing nations like North Macedonia, Albania, and Serbia, FL is more prevalent in the early stages of the supply chain due to inadequate infrastructure, inefficient storage systems, and low food literacy levels. These disparities highlight the importance of region-specific interventions to combat food wastage.

Contributions to Sustainability and the SDGs

The findings of this study align closely with several Sustainable Development Goals (SDGs), particularly:

SDG 2: Zero Hunger: Reducing FW and FL can improve food availability, addressing hunger and food security, especially in resource-constrained regions.

SDG 12: Responsible Consumption and Production: This research supports sustainable consumption and production patterns by promoting food literacy and efficient supply chains, we align closely with SDG 12.3, which aims to halve global food waste per capita at the retail and consumer levels, and to reduce food losses along production and supply chains by 2030. The commitment to this goal is exemplified by the efforts of the Champions 12.3 coalition, a global initiative driving action toward this target. Since its inception during the UNEA side event in 2016 in Kenya, the coalition has been working diligently to mobilize stakeholders, raise awareness, and implement strategies to address FW and FL on a global scale.

SDG 13: Climate Action: Mitigating FW and FL reduces greenhouse gas emissions, contributing to global efforts to combat climate change.

SDG 6: Clean Water and Sanitation and SDG 15: Life on Land: Minimizing resource wastage alleviates pressure on water and land resources, protecting ecosystems.

Key Findings and Contributions

1.Food Literacy: Enhancing food literacy through targeted awareness campaigns and food packaging innovations, such as expiration date indicators and eco-labels, offers a viable pathway to mitigate FW and FL. This approach is particularly impactful in developing nations, where projected improvements in food literacy levels could significantly reduce resource wastage.

2.Citizen Science and Eco-labels: Incorporating citizen science initiatives and detailed eco-labeling systems can empower communities and consumers to actively engage in reducing FW and FL. These tools not only enhance transparency but also integrate the Water-Energy-Food-Ecosystem (WEFE) nexus into decision-making processes.

3.Policy Implications: Policymakers must prioritize infrastructural investments in developing nations and consumer education in developed nations to address the distinct drivers of FW and FL. Collaborative efforts across supply chain stakeholders are essential for scaling sustainable practices.

Future Prospects

The integration of emerging technologies, such as machine learning, IoT, and blockchain, offers significant potential for improving FW and FL models. These innovations can enhance monitoring, traceability, and predictive capabilities, making supply chains more efficient and resilient. Furthermore, food literacy campaigns rooted in citizen science and awareness programs can drive behavior change, aligning public actions with the global goals of sustainability.

By identifying critical gaps in current models and proposing actionable solutions, this study contributes to advancing sustainable food systems. Addressing FW and FL through holistic, region-specific strategies will not only conserve resources but also support the achievement of multiple SDGs. This approach reduces the environmental burden of food systems while promoting equitable access to resources and fostering a sustainable future.

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