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INCORPORATING NEXUS ECOLABELS INTO HOUSEHOLD LEVEL FOOD WASTE MITIGATION STRATEGIES – ENVIRONMENTAL PERSPECTIVES FROM LIFE CYCLE ASSESSMENT

UKLJUČIVANJE NEKSUS EKO OZNAKA U STRATEGIJE ZA SMANJENJE OTPADA HRANE NA NIVOU DOMAĆINSTVA – EKOLOŠKE PERSPEKTIVE IZ PROCENE ŽIVOTNOG CIKLUSA

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ABSTRACT

This study provides a comprehensive evaluation of the economic and environmental impacts of food waste reduction through the implementation of Smart NEXUS Ecolabels. Employing the JRC Food Waste Prevention Calculator, the analysis centers on a optimistic-case scenario wherein household food waste is curtailed by 20%. The results reveal that mitigating food waste at this scale yields substantial benefits, with each ton of food waste prevented equating to the conservation of approximately 78 meals, reduction of 323 kg CO_2 equivalent emissions and an estimated cost savings of 133 euros in production and waste management expenditures. Extrapolating these findings to the EU's aggregate annual food waste, the potential large-scale impact is profound, encompassing 4.6 billion meals saved, 19.1 million metric tons of CO_2 equivalent emissions mitigated, and an estimated economic benefit of 7.85 billion euros. The environmental impact assessment, conducted across 16 midpoint categories, underscores the pivotal role of targeted food waste prevention strategies in curbing pollution, conserving natural resources, and bolstering food security. These findings substantiate the transformative potential of Smart NEXUS Ecolabels in facilitating systemic reform, reinforcing the necessity of embedding food waste reduction measures within broader sustainability frameworks to enhance resource efficiency at scale.
***Keywords**: sustainability assessment; circular economy; life cycle assessment; resource efficiency.*

REZIME

Ova studija pruža sveobuhvatnu procenu ekonomskih i ekoloških uticaja smanjenja otpada od hrane kroz primenu Smart NEKSUS Ecolabels. Koristeći JRC kalkulator za prevenciju otpada od hrane, analiza se usredsređuje na scenario optimističnog slučaja u kojem se bacanje hrane iz domaćinstva smanjuje za 20%. Rezultati otkrivaju da ublažavanje rasipanja hrane na ovoj skali donosi značajne koristi, pri čemu se svaka sprečena tona otpada od hrane izjednačava sa očuvanjem približno 78 obroka, smanjenjem emisije CO_2 ekvivalenta od 323 kg i procenjenom uštedom troškova od 133 evra u proizvodnji i troškovima upravljanja otpadom. Ekstrapolirajući ove nalaze na ukupno godišnje rasipanje hrane u EU, potencijalni uticaj velikih razmera je dubok, obuhvatajući 4,6 milijardi ušteđenih obroka, smanjene emisije ekvivalenta CO_2 od 19,1 miliona metričkih tona i procenjenu ekonomsku korist od 7,85 milijardi evra. Procena uticaja na životnu sredinu, sprovedena u 16 srednjih kategorija, naglašava ključnu ulogu ciljanih strategija za prevenciju rasipanja hrane u suzbijanju zagađenja, očuvanju prirodnih resursa i jačanju bezbednosti hrane. Ovi nalazi potkrepljuju transformativni potencijal Smart NEKSUS ekoloških oznaka u olakšavanju sistemske reforme, jačajući neophodnost ugrađivanja mera za smanjenje rasipanja hrane u šire okvire održivosti kako bi se povećala efikasnost resursa.
***Ključne reči**: procena održivosti; cirkularna ekonomija; procena životnog ciklusa; efikasnost resursa.*

INTRODUCTION

Food waste is a pressing global issue with profound environmental, economic, and social ramifications (*Schanes K., et al 2018*). The 2024 Food Waste Index Report of Food and Agriculture Organization (FAO) estimates that nearly 1.05 billion of tonnes of food are lost or wasted globally, exacerbating greenhouse gas emissions (*FAO 2021*), depleting natural resources (*Damiani M., et al, 2021*), and worsening food insecurity (*Wang Y., et al, 2021*). Recognizing this challenge, the United Nations has included food waste reduction as part of its Sustainable Development Goals (SDGs). Specifically, SDG 12.3 aims to halve global food waste per capita at the retail and consumer levels by 2030. In the European Union (EU) alone, approximately 59 million tons of food are squandered annually (*Eurostat, 2024*), equating to an economic loss of around €143 billion (SWD (2023)421). This significant waste not only intensifies environmental concerns (*Amicarelli, V., et al., 2021*), but also highlights inefficiencies in food distribution (*Barrera, E. L., and Hertel, T., 2020*) and consumption patterns (*Attiq, S., et al., 2021*). Addressing this challenge necessitates a multifaceted strategy (*Slorach, P. C., et al., 2019*) that integrates technological advancements (*Tsang, Y. P., et al., 2019; Jagtap, S., et al., 2019; Yan, B., et al., 2016; Engelseth, P., et al., 2018*), policy reforms (*Cattaneo, A., et al., 2020a; Qu, S., and Ma, H., 2022; Mesiranta, N., et al., 2021; Cattaneo, A., et al., 2020b*), consumer education (*Simões, J., et al., 2022; Varese, E., et al., 2022*), and enhanced supply chain management (*Annosi, M. C., et al., 2021; Ciccullo, F., et al., 2020; Sarkar, B., et al., 2022*).

A range of innovative solutions has been developed to mitigate food waste at various points within the supply chain (*Da Costa, T. P., et al., 2022*). Smart packaging technologies (*Ganeson, K., et al., 2023*), including intelligent sensors and time-temperature indicators (*Lehn, F., et al., 2023*), enable real-time monitoring of food freshness (*Pandian, A. T., et al., 2020*), thereby extending shelf life and minimizing spoilage (*Kitanovski, V. D., et al., 2023*). Digital traceability systems, such as blockchain technology (*Kopanaki, E., et al, 2021*), enhance transparency by allowing stakeholders to track food products from production through consumption, reducing inefficiencies and losses. Furthermore, artificial intelligence (AI) and big data analytics (*Onyeaka, H., et al., 2023*) optimize inventory management by improving demand forecasting, thereby reducing overproduction and surplus food waste (*Elgalb, A., and Gerges, M., 2024*).

Among these strategies, ecolabeling (*Zeng, T., et al., 2021*) has emerged as an effective tool for educating consumers and fostering sustainable food choices (*Flanagan, A., and Priyadarshini, A. 2021*). Smart ecolabels communicate critical information regarding the environmental impact of food products (*Szymkowiak, A., et al., 2024*), empowering consumers to make informed purchasing decisions. By leveraging digital platforms (*Hassoun, A., et al., 2023*), these ecolabels enhance consumer engagement and awareness of the resource-intensive nature of food production.

The Smart NEXUS Ecolabels represent a novel approach to addressing food waste through a citizen science-driven framework. Designed to enhance food literacy, these ecolabels highlight the interconnectedness of the Water-Energy-Food-Ecosystem (WEFE) Nexus (*Correa-Cano, M., et al., 2022*), with an emphasis resources and land use and climate considerations. Unlike conventional ecolabels, Smart NEXUS Ecolabels incorporate digital technology to facilitate full traceability across the food supply chain, reinforcing transparency and trust among producers, suppliers, and consumers.

This study evaluates the effectiveness of Smart NEXUS Ecolabels in reducing food waste by analyzing their environmental impact using a life cycle assessment (LCA) model (*Uhlig, E., et al., 2025*). The assessment focuses on the trade-offs involved in food production (*Antle, J. M., and Valdivia, R.O., 2020*), particularly for animal-based and all packed products, given their complex life cycles and significant environmental footprints (*Detzel, A., et al., 2021*). By enhancing consumer awareness and leveraging advanced technological innovations, Smart NEXUS Ecolabels helps foster a more sustainable and transparent food supply chain. Incorporating a strong food literacy element, these ecolabels equip policymakers with data-driven insights to develop and enforce more effective strategies that promote sustainability in the food sector.

Nomenclature:

CC – Climate change in units of Kilograms of CO_2 equivalent (kg CO_2 eq)
OD – Ozone depletion in units of Kilograms of CFC-11 equivalent (kg CFC-11 eq)
PM – Particulate Matter in units of Comparative Toxicity Units for human health (CTUh)
IRHH – Ionizing radiation, in units of Comparative Toxicity Units for human health (CTUh)
POFHH – Photochemical ozone formation, human health in Disease incidences
A – Acidification in units of Kilobecquerels of Uranium-235 equivalent (kBq U235)
TE – Terrestrial eutrophication in units of Kilograms of non-methane volatile organic compounds equivalent (kg NMVOC eq)
FWE – Freshwater eutrophication in units of Moles of hydrogen ions equivalent (mol H^+ eq)
ME – Marine eutrophication in units of Moles of nitrogen equivalent (mol N eq)
WU – Water use in units of Kilograms of phosphorus equivalent (kg P eq)
LU – Land use in units of Kilograms of nitrogen equivalent (kg N eq)
RUF – Resource use, fossil in units of Comparative Toxicity Units for ecosystem (CTUe)
RUMM – Resource use, minerals and metals in units of Points (Pt)
HTC – Human toxicity, cancer effects in units of Cubic meters of world-equivalent water deprived (m^3 world eq. deprived)
HTNC – Human toxicity, non-cancer effects in units of Megajoules (MJ)
FET – Freshwater ecotoxicity in units of Kilograms of antimony equivalent (kg Sb eq)
SP – Single Point Points (Pt)
NEXUS – An integrated approach addressing the interconnections between water, energy, food, and ecosystems to enhance sustainability.
WEFE Nexus dimension – The Water-Energy-Food-Ecosystem Nexus framework used to evaluate environmental, economic, and resource interdependencies.
JRC – Joint Research Centre, the European Commission's science and knowledge service, which provides tools such as the Food Waste Calculator used in this study.

MATERIAL AND METHOD

Smart NEXUS Ecolabels

The Smart NEXUS Ecolabels approach is primarily guided by the WEFE Nexus dimensions, with a targeted emphasis on Key Performance Indicators (KPIs) for food production. These KPIs assess efficiency, sustainability, and overall effectiveness throughout the supply chain within the ecosystem component, while deliberately excluding factors such as ecosystem services and biodiversity.

These ecolabels are designed for a broad spectrum of food products; however, their applicability is constrained in scenarios where packaging is absent, such as loose fruits and vegetables, which are frequently sold unpackaged in various markets. The Smart NEXUS Ecolabels feature an advanced adhesive external label integrated with digital technology. This seamless digitalization facilitates comprehensive traceability across the entire food supply chain, empowering consumers, suppliers, and producers with real-time access to detailed product information, thereby enhancing transparency and informed decision-making.

The primary objective of the Smart NEXUS Ecolabels is to enhance consumer comprehension of food literacy and environmental sustainability, particularly for individuals with limited awareness of the resource-intensive nature of food production. To facilitate meaningful engagement, we developed a life cycle assessment (LCA) model analyzing the environmental impact of one ton of food waste. This model provides a comprehensive and transparent evaluation of the trade-offs associated with food production, contextualized within the Water-Energy-Food-Ecosystem Nexus framework.

This assessment focused on the LCA design of all packaged food products, including animal-based ones, recognizing their more complex life cycles and the need for a detailed analysis. Additionally, the study highlights the limitation of Smart NEXUS Ecolabels, which are currently applicable only to unpackaged food—predominantly plant-based products—thus reinforcing the importance of assessing packaged food products.

The evaluation was carried out utilizing the Food Waste Prevention Calculator, a tool developed by the Joint Research Centre (JRC). The Life Cycle Assessment model adheres to the four-phase framework established by ISO 14040/14044, ensuring a systematic and standardized approach. The overall structure of the LCA model, encompassing the various stages of the food supply chain, is illustrated in Figure 1.

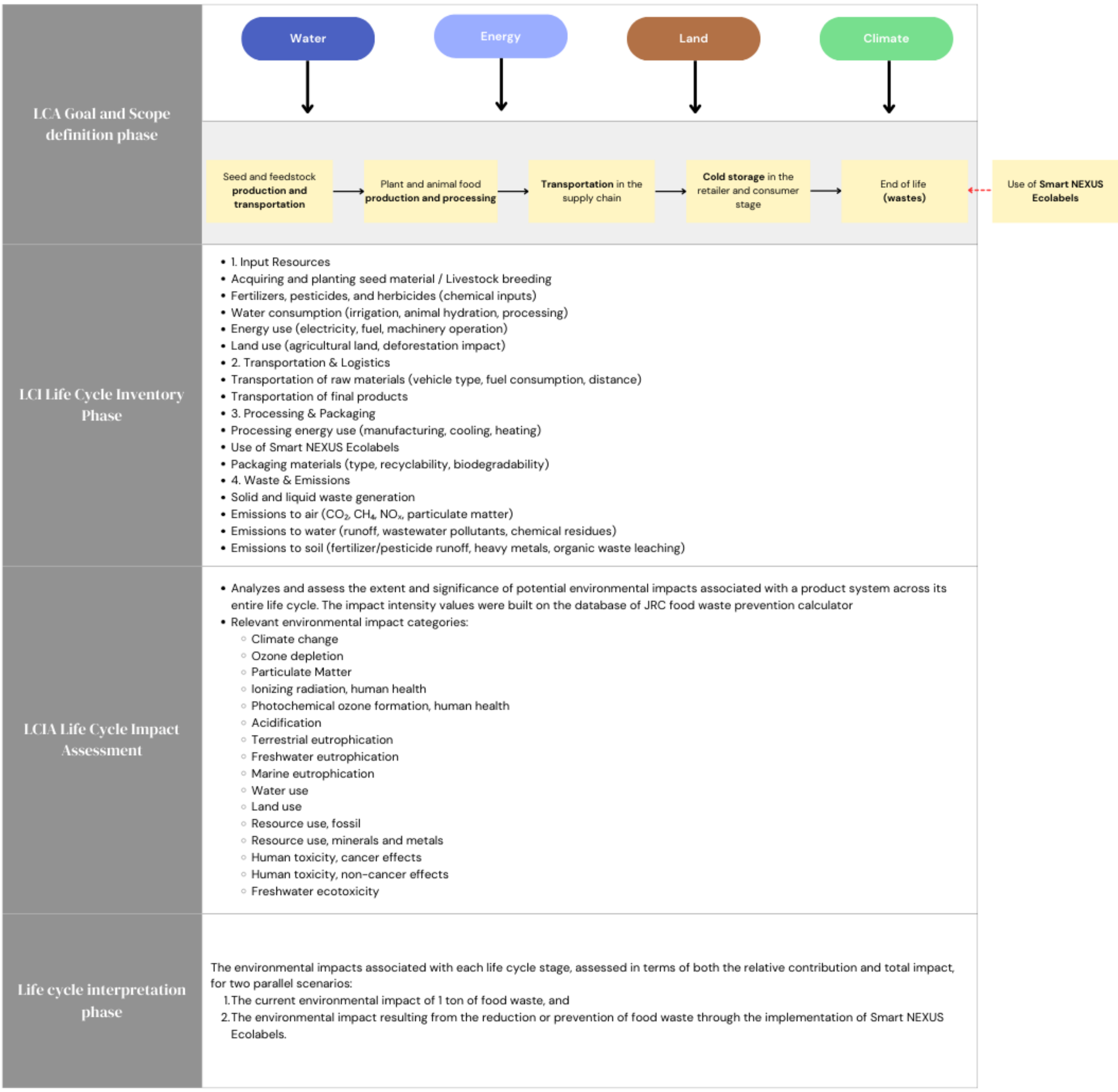

Fig. 1. Comprehensive LCA model structure: Integrating Life Cycle Stages of food production, supply chain, and waste management

Goal and scope

Geographical and Temporal Scope

The geographical scope of this study is the European Union (EU). The temporal scope consists of a combination of gathered data from 2023 on food waste levels and a projected one-year scenario estimating the potential impact of Smart NEXUS Ecolabel adoption. The scenario assumes a 20% reduction in household food waste, based on estimated acceptance and efficiency rates of ecolabel implementation.

Data Sources and Data Quality

The primary data sources include Eurostat and the third reporting obligation on food waste in the EU, which presents sector-specific data following the NACE Rev.2 classification, excluding food losses (such as unharvested crops or food not authorized for marketing due to safety concerns). Given that the data originates from established institutions and official reporting mechanisms, it is considered to be of high quality and reliability. However, no direct field data collection was conducted for this study.

Uncertainty Analysis

The main sources of uncertainty stem from the projection-based nature of the study. The 20% reduction scenario is an optimistic estimate based on assumed consumer adoption rates and behavioral changes, which can vary depending on socioeconomic and regulatory factors. Additionally, variations in food waste generation patterns across EU member states, discrepancies in national reporting methodologies, and potential future policy changes contribute to uncertainty in the model outcomes. To account for these uncertainties, sensitivity analyses can be applied in future research to test different ecolabel adoption rates and external influencing factors.

This model adopts a cradle-to-grave perspective (*Zhu, J., et al., 2023*), encompassing all stages of the food supply chain to ensure a comprehensive assessment. It accounts for diverse material production processes (*Chung, M. M. S., et al., 2021*), transportation systems (*Striebig, B., et al., 2019*), and end-of-life treatments, providing a holistic view of food waste's environmental footprint. The specific LCA stages considered in this model are depicted in Figure 2.

Beyond assessing the life cycle of food waste, this study also incorporates Smart NEXUS Ecolabels as a novel approach. By utilizing advanced digital technologies and behavioural insights, these ecolabels aim to mitigate food waste at the household level and strengthen sustainability efforts across the food supply chain.

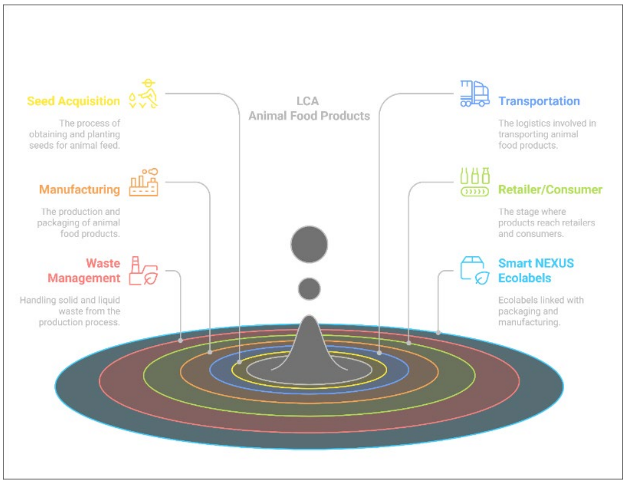

Fig. 2. Cradle-to-Grave LCA model for animal food products including Smart NEXUS Ecolabels as an innovative solution for food waste reduction

The system boundary encompasses six key stages: Seed Acquisition, Manufacturing and Packaging, Transportation, Storage at Retail and Household Levels, Waste Management, and Smart NEXUS Ecolabels. Seed Acquisition includes water, energy, and land use, along with transportation in two phases: (i) Resource use and transportation for seed planting, harvesting, and feed production. (ii) Transportation of fodder to farmlands. Manufacturing accounts for water, energy, and land use for livestock, as well as processing to obtain animal-based food products and packaging. Additionally, indirect environmental impacts such as fertilizer production, fuel use in agricultural machinery, direct field emissions, and land-use change are inherently integrated into the assessment through the JRC Food Waste Calculator, which applies the Environmental Footprints 4.0 methodology. This ensures a comprehensive evaluation of the environmental burdens associated with food waste from animal-based products . Storage at the Retailer and Household Levels considers electricity consumption. Transportation accounts for all transport activities across all stages. Waste Management includes all the waste generated throughout the system. Smart NEXUS Ecolabels cover the resources required for ecolabel production and their transportation to manufacturing facilities. This structured approach ensures a comprehensive assessment of food waste and its environmental implications, reinforcing the role of Smart NEXUS Ecolabels in fostering sustainability across the food supply chain.

Life Cycle Inventory LCI and Life cycle impact assessment LCIA

The Life Cycle Assessment (LCA) model inventory for the production, supply, storage, and treatment of 1 ton of food waste comprehensively incorporates all essential input and output flows, ensuring a robust and precise quantification of environmental impacts. The methodology employed is aligned with the Joint Research Centre (JRC) Food Waste Prevention Calculator, providing a scientifically validated framework for evaluating food waste management strategies.

The Life Cycle Impact Assessment (LCIA) phase adheres strictly to the internationally recognized ISO 14040/14044 standards, ensuring methodological consistency, reliability, and comparability of results.

The impact assessment method applied is the Environmental Footprint (version 3.0), which defines sixteen midpoint impact categories as recommended by the European Commission (*EC-JRC, 2019; European Commission, 2013*). Their inclusion ensures a comprehensive and multidimensional evaluation of the potential environmental burdens associated with food waste across its entire life cycle.

Interpretation

The successful implementation of the Smart NEXUS Ecolabels to reduce food waste will yield environmental benefits by avoiding the impacts associated with the production and disposal of saved food items. This reduction in waste helps mitigate the environmental burdens linked to food production, processing, and transportation, as well as the impacts of waste management operations. However, the action may also result in additional environmental impacts due to the energy and material resources consumed during the implementation of the ecolabeling process.

To assess the environmental benefits of food waste reduction initiatives, the life cycle impacts of the following three key components are considered: A) Avoided Impacts from Producing and Distributing the Saved Food Items. This component captures the environmental savings associated with the food that is prevented from being wasted, based on the quantities and types of food saved and the specific stage in the Food Supply Chain (FSC) where the waste reduction occurs. The calculations rely on data provided by the user as described by (*De Laurentiis, V. et al., 2020*) and draw on the environmental impacts of 32 food commodities following (*Sinkko et al., 2019*), representing the consumption patterns of an average European citizen. These impacts are estimated through an LCA model using SimaPro 8.5 software (*Pré-Sustainability, 2018*), covering six stages of the FSC: agricultural production, processing, packaging, retail, use, and end-of-life stages, as outlined in (*Notarnicola et al. 2017; Sinkko et al. 2019; and Crenna et al. 2019*). B) Avoided Impacts from Food Waste Disposal. This component evaluates the environmental effects associated with the disposal of food waste, considering five primary waste management options: landfill, composting, incineration, anaerobic digestion, and wastewater treatment (including liquids wasted through the sink). The data used for this calculation are derived from (*Notarnicola et al. 2017*). C) Environmental Impacts from Implementing Action. This component estimates the environmental impacts arising from the execution of the food waste prevention action. The assessment considers three proxies: transport distances, electricity consumption, and paper usage (measured by the number of leaflets produced). These are then combined with average impact factors related to: 1 km of transport by passenger car, 1 kWh of electricity consumption, and the production of 1 A4 printed page. Background data for this analysis are taken from the Ecoinvent 3 database (*Wernet et al., 2016*).

Calculation of net environmental savings is performed by adding the impacts from A and B, then subtracting the impacts from C. This method allows for the identification of potential environmental trade-offs resulting from the implementation of the food waste prevention action, ensuring that the benefits of reducing food waste outweigh the impacts associated with the action itself. This approach helps to avoid situations where the environmental cost of implementing the action exceeds the environmental benefits derived from the reduction of food waste.

LCA Framework Structure, Assumptions and Limitations

Our LCA model is built upon the JRC Food Waste Prevention Calculator, which inherently limits its ability to quantify food waste at each specific stage of the food supply chain (FSC). Additionally, conducting sensitivity analyses to compare the environmental and economic impacts of one ton of wasted food with conventional benchmarks is not feasible within this framework. However, these critical limitations are effectively mitigated through the implementation of Smart NEXUS Ecolabels. The primary objective of this technology is to enhance food literacy, thereby actively reducing food waste at the final stage of the FSC—households—where consumer behavior plays a pivotal role in waste generation.

Validation: Case Study of Smart NEXUS Ecolabels Impact Assessment in EU

Definition of Goal and Scope

The primary objective of this assessment is to evaluate the potential environmental impact of food manufacturing, with a focus on its direct translation into food waste generation, based on a defined functional unit. The functional unit for this study was established as the production of 1 ton of food, which will subsequently be converted into 1 ton of food waste, maintaining the same composition ratio across food categories. This approach allows for a detailed analysis of the environmental implications of food waste from production processes, taking into account the specific food types and their respective proportions.

In this context, a medium-case scenario was developed, assuming a 20% reduction in environmental impact due to the implementation of Smart NEXUS Ecolabels. The Smart NEXUS Ecolabels were anticipated to mitigate the environmental impacts associated with food waste by promoting sustainable practices and reducing waste generation. The reduction factor was applied based on the assumption that the implementation of the ecolabels would lead to more efficient food production and consumption, thereby contributing to the reduction of both direct and indirect environmental burdens.

The composition of the 1 ton of food waste generated was based on the results of the food waste categorization outlined in JRC Technical Report (Patinha Caldeira, C., et al., 2019), which is visually represented in Figure 3 below. This figure illustrates the relative proportion of food categories within the generated food waste, offering a clear overview of the waste composition across different food types, from one side and the potential impact of Smart NEXUS Ecolabels on the prevention of FW.

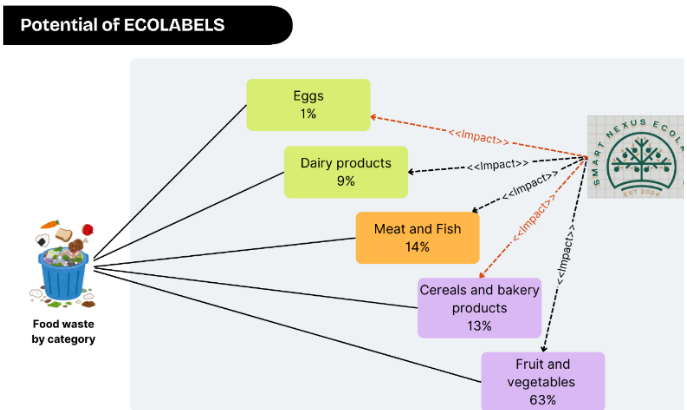

Fig. 3. Potential impact and economic feasibility of investing in and implementing Smart NEXUS Ecolabels for food waste reduction across food waste categories

Furthermore, the environmental impact of the Smart NEXUS Ecolabels was assessed based on the above-mentioned limitations related to the unpacked food products category. These limitations were considered crucial for accurately determining the impact reduction potential, as unpackaged food products may present unique challenges in terms of waste reduction and resource optimization.

The suggested innovative technology for food waste reduction can be seamlessly implemented across all food categories, given that the ecolabels are designed to be safe and compatible with a wide range of packaged food products. However, the impact of the ecolabels varies depending on the specific food category. As indicated by the red lines in Figure 3, the ecolabels demonstrate the smallest impact in categories where the proportion of packaged food is low, or where the percentage of total food waste generated by that category is minimal. In these cases, the technology's potential to reduce food waste becomes more questionable. This variability in impact can be visually assessed by examining the total food saved in kilograms, which is presented in Table 1. The impacts were calculated by integrating the reduction factor for the ecolabels within the context of the functional unit, offering a comprehensive evaluation of the potential environmental savings derived from food waste prevention strategies.

This methodology ensures that the analysis of the Smart NEXUS Ecolabels is robust, taking into account food waste composition, the efficacy of eco-labeling interventions, and their broader environmental implications, while adhering to established life cycle assessment (LCA) principles.

Life Cycle Inventory and scenario calculation

The life cycle inventory (LCI) inputs for the production of 1 ton of food, maintaining the same composition as the generated food waste in the European Union (EU) across various food categories, were provided by the developers of the JRC Food Waste Prevention Calculator. These inputs align with the methodology and data described in section 3.1.2, ensuring consistency and comparability in the environmental impact assessment.

To evaluate the potential impact reduction in food waste, a medium-case scenario was established, assuming a 20% reduction in the environmental burden of food waste. This reduction factor was calculated based on data from (Eurostat), which provides detailed information on the percentage of food waste generated at each link of the Food Chain (FC), visually represented in Figure 4.

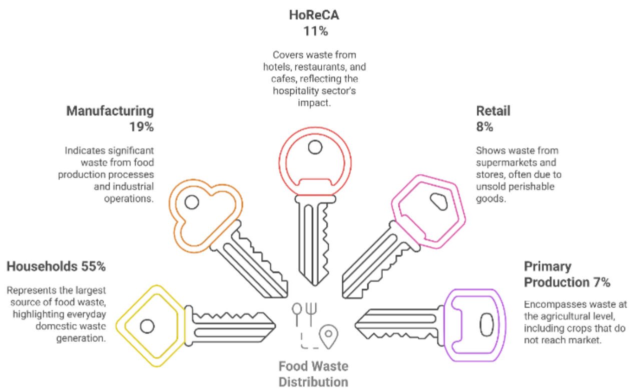

Fig. 4. Understanding and identifying key sources of food waste generation

The impact of the Smart NEXUS Ecolabels is anticipated to be most significant at the final stage of the food chain (FC), specifically within households, which account for a substantial proportion of total food waste generation. The Smart NEXUS Ecolabels can play a pivotal role in this context by encouraging more responsible consumption behaviors, such as purchasing in more appropriate quantities, reducing excess packaging, and increasing awareness about food waste reduction strategies.

The input inventory data used for calculating the reduction factor associated with the Smart NEXUS Ecolabels was derived by estimating the mass of materials required to produce 1,000 Smart NEXUS Ecolabel plastic stickers, which are intended for use in packaging 1 ton of food products (with an average product weight of 1 kg).

For the production of 1,000 stickers, each with dimensions of 105 mm in width and 59.4 mm in height, it was determined that 100 A4-sized sheets of plastic are required. The average mass of a plastic A4 sheet is approximately 5 grams. It depends on the type of polymer, but based on the findings of (Marczak Halina 2022) the energy consumption for production of plastic, reported in the literature, varies a lot: PE-LD: 64.6–92 MJ/kg, PP: 64–111.5 MJ/kg, PS: 70.8–118 MJ/kg, PC: 78.2–117.4 MJ/kg, PVC: 52.4–79.5 MJ/kg (Iwko, J., and Wróblewski, R., 2019). For the purpose of this calculation, an average energy requirement of 80 MJ per kg was assumed.

Thus, the energy required to produce the plastic for 1,000 stickers (equivalent to 0.5 kg of plastic) is calculated as:

$$80MJ \times 0.5 = 40MJ \qquad (1)$$

To convert this energy into kilowatt-hours (kWh):

$$40MJ \div 3.6 = 11.11kWh \qquad (2)$$

This energy estimate represents the consumption associated with the production of the Smart NEXUS Ecolabel plastic stickers. In addition to the material production energy, the transportation distance for the Smart NEXUS Ecolabels was assumed to be 100 km, which represents a typical logistics scenario. The cost of producing one sticker was estimated at €0.12 per unit, considering both material and production costs.

The prevented food loss resulting from the implementation of the Smart NEXUS Ecolabels is quantified in terms of kilograms per food category. These reductions are presented in Table 1, which provides a detailed breakdown of the food categories affected by the scenario, including the estimated reduction in food waste through the FSC.

By integrating these data points, this analysis aims to provide a comprehensive evaluation of the environmental impact reductions achievable through the adoption of Smart NEXUS Ecolabels, offering a holistic view of the benefits associated with this food waste prevention strategy.

RESULTS AND DISCUSSION

Achieving sustainable food production is essential for combating climate change, alleviating water scarcity, reducing pollution, and restoring degraded ecosystems. The livestock sector, which includes meat, dairy, and seafood production, significantly contributes to greenhouse gas emissions through various processes. A major source is methane release from enteric fermentation during digestion (Scoones, I., 2022; Grossi, G. et al., 2018). Additional emissions arise from, land-use changes, crop cultivation for animal feed, and the energy demands of intensive farming systems (Cheng, M., et al., 2022).

Similarly, crop and vegetable production play a substantial role in direct greenhouse gas emissions. These result from nitrous oxide release due to fertilizer and manure applications, methane emissions from rice paddies, and carbon dioxide from fuel-dependent agricultural machinery (Mantoam, E. J., et al., 2020; Lovarelli, D., & Bacenetti, J., 2019).

Water usage and eutrophication are critical measures of food production's environmental footprint, with agriculture accounting for approximately 70% of global freshwater withdrawals and water pollution (Xue, X., & Landis, A. E., 2010; Scardigno, A., 2019). The leaching of excess nutrients into waterways disrupts ecological balance, primarily due to nitrogen and phosphorus accumulation, which deteriorates aquatic biodiversity and water quality (Lu, Y., et al., 2015; Grizzetti, B., et al., 2021).

According to the matrix presented in Table 1, which outlines the medium-case scenario assuming a 20% reduction in food waste at the final stage of the food chain (households), the associated economic and environmental impacts were systematically evaluated using the JRC Food Waste Prevention Calculator. This tool enables a comprehensive assessment of the benefits derived from food waste reduction strategies, quantifying their impact across multiple environmental and economic parameters.

The total mass of saved food products was 60.34 kg at the household stage of the food supply chain. The analysis focuses on the environmental impact across 16 midpoint impact categories, as defined by the Environmental Footprint (EF) methodology. The results of this impact assessment are systematically presented in Table 2, which illustrates the environmental implications of food waste prevention across these 16 midpoint categories.

These categories, aligned with EF 3.0 recommendations, include key indicators such as climate change, resource depletion, water and land use, eutrophication, acidification, human toxicity, and ecotoxicity, among others. The data presented in Table 2

Table 1. Detailed calculations of saved food products across categories at the household stage – Medium scenario (20% food waste reduction)

Food waste category at household sector 55% of 1 ton of food waste	Mass and Percentage of packed food	Mass of food calculated in 20% scenario	Total mass of food saved
Fruit and vegetables 55% of 630 kg = 346.5 kg	346 kg of which 50% are packed	173 kg with 20% reduction rate	34.6 kg
Cereals and bakery 55% of 130 kg = 71.5 kg	71.5 kg of which 10% are packed	7.15 kg with 20% reduction rate	1.43 kg
Meat and meat products 55% of 100kg = 55kg	55 kg of which 90% are packed	49.5 kg with 20% reduction rate	9.9 kg
Fish and seafood products 55% of 40 kg = 22 kg	22 kg of which 90% are packed	19.8 kg with 20% reduction rate	4.4 kg
Dairy products 55% of 90 kg = 49.5 kg	49.5 kg of which 90% are packed	44.55 kg with 20% reduction rate	8.91 kg
Eggs 55% of 10 kg = 5.5 kg	5.5 kg of which 100% are packed	5.5 kg with 20% reduction rate	1.1 kg

provide a detailed quantification of how the implementation of Smart NEXUS Ecolabels in the household sector contributes to mitigating environmental burdens, reducing greenhouse gas emissions, conserving natural resources, and minimizing pollution.

The Impact of Food Saved represents the most significant contribution to the overall environmental benefit, as it encompasses the avoided emissions and resource use associated with food production, processing, packaging, transportation, and storage. Since food production is a major contributor to global environmental pressures, including land degradation, water use, and greenhouse gas emissions, preventing food from becoming waste leads to con siderable sustainability gains.

Table 2. Environmental Assessment: Impacts and savings across 16 evaluated impact categories

Indicator	Unit	Impact of action	Impact of avoided treatment	Impact of saved food	Total
Climate change	kg CO_2 eq	-7.17E+01	3.63E+01	3.60E+02	3.25E+02
Ozone depletion	kg CFC-11 eq	-8.97E-06	2.08E-07	3.34E-04	3.25E-04
Particulate Matter	CTUh	-3.66E-06	1.04E-07	5.10E-05	4.74E-05
Ionizing radiation, human health	CTUh	-5.20E+00	1.14E-01	4.60E+00	-4.80E-01
Photochemical ozone formation, human health	Disease incidences	-2.28E-01	1.96E-02	6.80E-01	4.72E-01
Acidification	kBq U^{235}	-3.59E-01	7.98E-03	7.06E+00	6.71E+00
Terrestrial eutrophication	kg NMVOC eq	-7.45E-01	2.39E-02	3.09E+01	3.02E+01
Freshwater eutrophication	mol H+ eq	-3.26E-03	3.03E-04	6.07E-02	5.78E-02
Marine eutrophication	mol N eq	-6.71E-02	7.61E-02	3.49E+00	3.49E+00
Water use	kg P eq	-2.09E+01	1.01E-01	4.21E+02	4.00E+02
Land use	kg N eq	-1.24E+03	3.61E+01	1.11E+04	9.90E+03
Resource use, fossil	CTUe	-1.21E+03	1.70E+01	1.77E+03	5.77E+02
Resource use, minerals and metals	Pt	-3.64E-04	1.32E-06	3.32E-04	-3.11E-05
Human toxicity, cancer effects	m^3 world eq. deprived	-4.63E-08	1.76E-09	2.03E-07	1.58E-07
Human toxicity, non-cancer effects	MJ	-9.74E-07	8.41E-08	7.86E-06	6.97E-06
Freshwater ecotoxicity	kg Sb eq	-1.69E+03	1.50E+02	1.28E+04	1.12E+04
Single Point	Pt	-9.61E-11	1.85E-11	7.54E-10	6.76E-10

In the Table 2., the relative contribution of each key component is systematically presented, illustrating the environmental impact distribution associated with the implementation of the Smart NEXUS Ecolabels. This assessment considers three primary aspects: The direct impact of the intervention (Impact of Action); The environmental benefits derived from avoiding food waste treatment (Impact of Avoided Treatment); The environmental savings achieved through food waste prevention (Impact of Food Saved). The environmental impact values were obtained using the JRC Food Waste Calculator, which applies the Environmental Footprints 4.0 methodology. In this assessment, negative values indicate environmental burdens, while positive values represent environmental savings (avoided burdens). This convention follows the output format of the JRC tool rather than standard LCA reporting, where negative values typically represent avoided impacts.

Each of these components plays a critical role in determining the net environmental effect of the proposed food waste reduction strategy. The Impact of Action accounts for the resources consumed and emissions generated in producing and implementing the Smart NEXUS Ecolabels, including, but not limited to, material production, energy use, and transportation. This encompasses a broader range of environmental flows, as assessed by the JRC Food Waste Calculator, ensuring a more comprehensive evaluation. Although this component introduces additional environmental burdens, it is expected to be significantly outweighed by the benefits derived from food waste reduction.

The Impact of Avoided Treatment reflects the environmental savings resulting from the reduction in waste management activities, such as landfill disposal, composting, incineration, or anaerobic digestion. By preventing food waste at the source, the need for energy-intensive and emissions-generating waste treatment processes is substantially reduced, leading to lower greenhouse gas emissions and minimized resource consumption.

Analyzing Tabe 2., it becomes evident that the Smart NEXUS Ecolabels yield a net-positive environmental impact, with the benefits of avoided food waste treatment and food saved far exceeding the initial environmental costs of implementing the system. This reinforces the efficacy and sustainability of proactive food waste prevention strategies as a means to mitigate environmental degradation while promoting resource efficiency within the food system.

The economic assessment of the implementation of Smart NEXUS Ecolabels, including the associated costs for their production, is comprehensively presented in Table 3. This analysis aims to quantify the financial feasibility and cost-effectiveness of the proposed intervention by evaluating both the expenses incurred in producing and deploying the ecolabels and the economic benefits resulting from food waste reduction.

Table 3. Economic assessment of prevented food waste per ton of generated food waste

Cost of action	-120 €
Savings from avoided treatment	7 €
Savings from avoided food production	246 €
Total net savings	133 €

As illustrated in Table 3, the findings indicate that the total net savings achieved through the implementation of Smart NEXUS Ecolabels can reach approximately €133 per ton of food waste prevented. This economic benefit is derived from multiple factors (Clare, G., et al., 2023; Martin-Rios, C., et al., 2020; De Menna, F., et al., 2018), including: Reduction in food procurement costs – By minimizing food waste at the consumer level, households and businesses experience a direct cost saving as they require less frequent purchases to meet the same consumption needs. Savings from avoided waste management costs – The reduction in food waste generation leads to lower expenditures on waste collection, transportation, and treatment, including landfill fees, composting, incineration, and anaerobic digestion costs. Optimized resource allocation – By improving food supply chain efficiency, businesses can streamline inventory management, reducing losses associated with unsold or expired products. Potential secondary economic benefits – Additional financial gains may arise from enhanced consumer engagement, brand reputation, and compliance with emerging sustainability policies aimed at reducing food waste. The economic viability of Smart NEXUS Ecolabels is further reinforced by the fact that the implementation costs are relatively low, primarily covering the production and application of the ecolabels. Given the significant financial savings achieved per ton of food waste prevented, the return on investment (ROI) for this sustainability-driven initiative is highly favorable (Ribeiro I., et al., 2017).

This initiative integrates citizen science to enhance food literacy and environmental awareness, particularly regarding resource consumption within the WEFE (Water-Energy-Food-Ecosystem) Nexus (Skawińska, E., and Zalewski, R. I. 2022). The effectiveness of this approach is further validated through the JRC calculator, which provides quantifiable metrics that support its role as a social driver within the sustainability framework of the NEXUS Ecolabels. For each ton of food waste prevented through this technology, approximately 78 meals are saved, equating to food security for an adult for 28 days. Additionally, every ton of food waste avoided translates to a reduction of 323 kg of CO_2 equivalent emissions and cost savings of 133 euros in food production and waste management. When scaled to the estimated annual food waste in the EU, approximately 59 million tons, the impact is substantial, Figure 5.

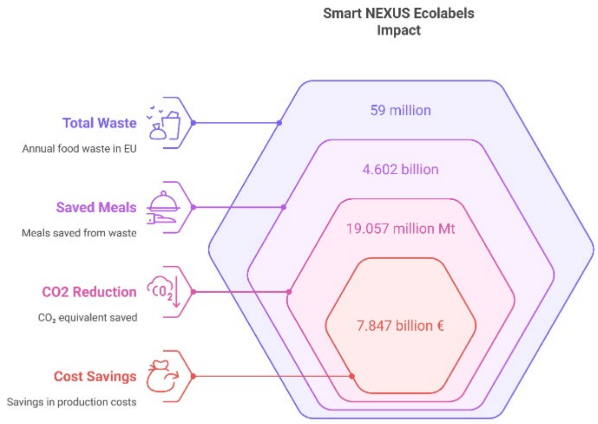

Fig. 5. Unlocking the transformative potential of Smart NEXUS Ecolabels in mitigating EU aggregate annual food waste: An estimation grounded in the 20% reduction scenario for wasted packaged food at the household stage

These findings highlight the transformative potential of the Smart NEXUS Ecolabels in fostering a more sustainable and efficient food system, reinforcing the importance of systemic change in addressing food waste at scale.

Despite common misconceptions, transportation-related emissions contribute only a small fraction of the food system's overall carbon footprint. The environmental impact of dietary choices and food waste far exceeds the significance of food miles (Qin, Y., & Horvath, A., 2021; Sasaki, Y., et al., 2021; Urbano, B., et al., 2022). Generally, animal-based foods have a considerably higher environmental footprint than plant-based alternatives, regardless of whether they are locally sourced or imported (Espinosa-Marrón, A., et al., 2022; Bryant, C. J., 2022; Xu, X., et al., 2021; Hilborn, R., et al., 2018). Consequently, reducing meat consumption or shifting toward lower-impact proteins such as poultry and eggs represents one of the most effective strategies for minimizing the environmental consequences of food production (Perignon, M., et al., 2016; Mertens, E., et al., 2019).

CONCLUSION

The findings of this study highlight the significant economic and environmental benefits of reducing food waste through the implementation of Smart NEXUS Ecolabels. The medium-case scenario, assuming a 20% reduction in household food waste, demonstrates the potential for meaningful impact when prevention strategies are effectively applied. Utilizing the JRC Food Waste Prevention Calculator, this study provides a comprehensive assessment of the benefits of food waste reduction, emphasizing its role in sustainability.

The environmental impact assessment, conducted across 16 midpoint categories under the Environmental Footprint methodology, underscores the far-reaching advantages of food waste prevention. Notably, the reduction in waste translates into considerable savings in meals, greenhouse gas emissions, and economic costs. On a larger scale, these findings demonstrate the transformative potential of targeted interventions in strengthening food security, mitigating climate impact, and improving resource efficiency across the EU.

The implementation of Smart NEXUS Ecolabels presents a pragmatic and data-driven solution for addressing food waste at its source. By fostering behavioral change among consumers and raising awareness of the environmental footprint of discarded food, this initiative supports the transition toward a more sustainable and resilient food system. Ultimately, these findings reinforce the urgency of integrating systemic food waste prevention measures within broader sustainability policies to optimize resource use and reduce environmental burdens at scale.

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