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Wholesale fruit and vegetable market in Milan: Turning food surpluses into environmental gains

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ABSTRACT

Food redistribution is increasingly recognized as a key strategy for tackling food waste and improving food security. However, a comprehensive assessment of its environmental impacts remains a challenge. This study fills this gap by investigating the role of food redistribution in minimizing waste, reducing production pressures, and mitigating the environmental impacts of the agri-food chain. In particular, this research focuses on mapping the flow of recovered food within the Ortomercato system, Italy's largest fruit and vegetable wholesale market, by third sector associations.

A comprehensive cradle-to-grave life cycle assessment was conducted to quantify the recovered fruit and vegetable products, assess their environmental impact, and estimate the associated environmental credits through the prevention of food waste.

The findings indicate that the production phase has the largest environmental impact, accounting on average for 63% of the total impact. The study employs a net balance approach to demonstrate the success of food recovery efforts, which have saved over 136 tonnes of food from the market over a 49-day period and generated environmental credits equivalent to 169 tonnes of CO_2 eq. per year. These results highlight the environmental impact of food redistribution and provide insights for operational optimization and the establishment of an environmental budget for the system. Furthermore, the potential for regulating these environmental credits and promoting the benefits of food redistribution through public channels is highlighted.

While the research addresses the mapping of food flows and their environmental impacts, there is a significant gap in the assessment of the socio-economic impacts associated with food redistribution. Further research is needed to understand how this practice affects local communities, economies and social dynamics, and to contribute to a more comprehensive assessment of its effectiveness.

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Nomenclature:

Food redistribution	Refers to the process of collecting and distributing food that would otherwise go to waste, to places where it can be used, such as food banks or shelters.
FLW: Food loss and food waste	Encompasses both the loss of food from the supply chain before it reaches the consumer and the waste of food by consumers and retailers.
Food donation	Food donation involves giving away wholesome food for human consumption to those in need, which helps to divert food waste.
Surplus food	Surplus food is edible food that is not sold or consumed and is instead redistributed to prevent it from becoming waste.
Waste streams	Waste streams in the study refer to the flow of specific waste types from their source through to recovery (biogas or composting).
Foody HUB & Ortomercato	Foody HUB is a space at the Milan General wholesale market called "Ortomercato" for collecting still-edible fruits and vegetables to redistribute to vulnerable people in Milan, as part of the city's food waste reduction efforts.
RECUP APS or RECUP	One of the most active non-profit Organizations of the Third Sector operating at the Foody Hub in Ortomercato (Milan, Italy) (https://associazionerecup.org/, last access: December 2nd, 2023).
Environmental impact Avoidance	refers to actions taken to reduce/prevent the environmental impacts and it is based on the carbon avoidance principle
SDG	SDG stands for Sustainable Development Goals, which are a collection of 17 global goals set by the United Nations General Assembly in 2015 for the year 2030. They are intended to be a "blueprint to achieve a better and more sustainable future for all".

1. Introduction

The scale of food wastage has reached unprecedented levels, with 14 percent of the world's food lost after it is harvested and before it reaches the shops (FAO, 2019). Despite the substantial global food production capacity to meet the demands of the world's population, more than 3,1 billion individuals continue to face persistent challenges in accessing an adequate and healthy diet, with over 690 million people experiencing chronic hunger (FAO, 2020). This situation not only represents missed opportunities to improve food security but also incurs an annual cost of 2.6 trillion USD for the environment, economy, and society (Gustavsson et al., 2011). Reducing food loss and food waste (FLW) stands as a fundamental imperative in the pursuit of sustainability (Minor, 2019; Narvanen, 2020; Weber and Khademian, 2008). Most of the global hunger occurs in low-income countries and the largest share of FLW occurs in middle- and high-income countries, but food insecurity and food waste can coexist within countries and regions (FAO, 2021; Lawrence and Friel, 2019). In the developed regions of Europe and North America, annual FLW account for 129 Mt and 168 Mt, respectively, while a significant portion, up to 12% of the population, continues to confront challenges related to food insecurity (Caldeira et al., 2019a).

According to FAO, fruits, and vegetables, including roots and tubers, are responsible for almost 45–50% of the waste. The highest volume of waste is documented in the realm of household consumption (De Laurentiis et al., 2018), despite the absence of precise monitoring for discarded items within the broader context of general and large-scale distribution markets. The United Nations Sustainable Development Goals (SDGs) encompass both the critical concerns of hunger and FLW on a global scale. Notably, SDG target 12.3 sets a specific objective to reduce per capita food waste at the retail and consumer levels by 50% before 2030, underscoring the international commitment to combatting these challenges for a more sustainable future (United Nations, 2023). Policy measures setting specific goals to cut food waste by half, encompassing fruits and vegetable waste, within the next years, are now often complemented by technological innovations aimed at streamlining the supply chain, minimizing losses in transportation and storage, and improving the alignment of supply with demand (Pasarín and Viinikainen, 2022).

The hierarchy pyramid ranks the preferred strategies (see Fig. 1), focusing first on prevention actions, followed by reuse pathways (European Commission, 2021a, 2021b). Concurrently, the notion of a circular economy, emphasizing more efficient resource utilization, has gained momentum. This involves recycling and composting organic waste, such as fruits and vegetables, to produce compost or biogas. Initiatives aimed at retrieving and distributing wholesome and safe food, frequently through donations, constitute crucial interventions preventing edible food from becoming waste. In this scenario, numerous stakeholders, often managed by nonprofit third sector associations, engage in a diverse range of interventions: gleaning networks, different types of food banks, community and charitable programs, shelters, soup kitchens, and social supermarkets (Milan Urban Food Policy Pact Monitoring Framework, 2021). Although food donation alone may not possess the capability to address the underlying causes of hunger or

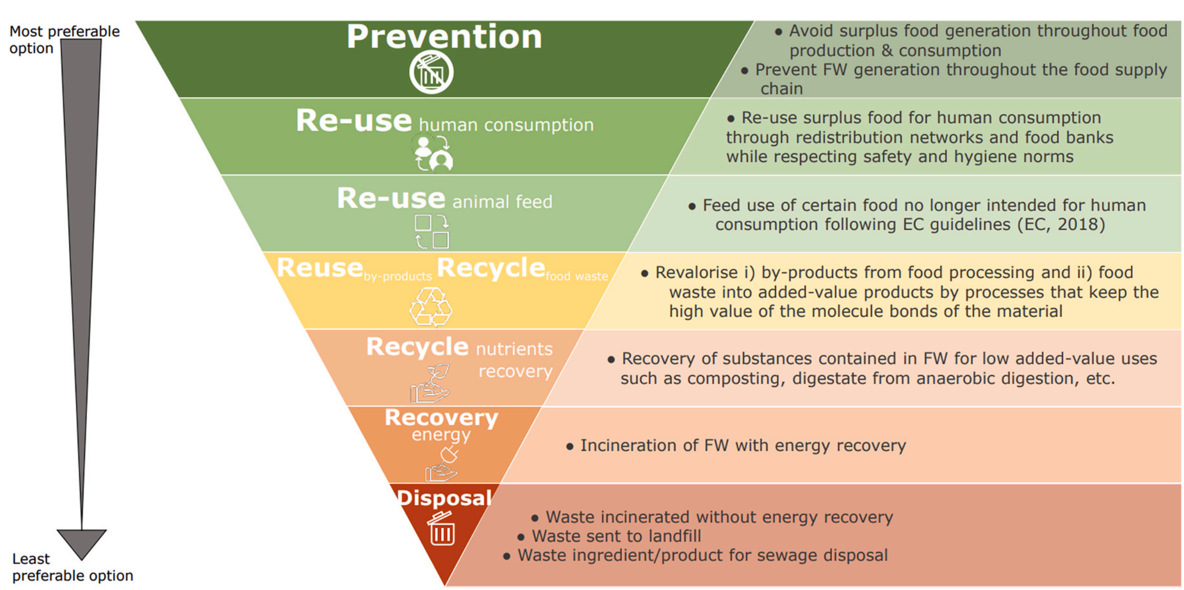


Fig. 1. Hierarchy for prioritization of food surplus, by-products, and food waste (FW) prevention strategies (European Commission, 2021a,b).

retail food waste, it holds the potential to serve as a short-term solution to mitigate both issues. In recent times (Riches, 2018), food donation has been criticized for shifting burdens from the public to the private sector and for its ineffective redistribution, mainly due to various barriers, such as the short shelf-life of perishable foods or the lack of organization needs. Concurrently, there is an acknowledgment of the presence of surplus food alongside a pressing need for effective strategies to facilitate its redistribution (Facchini et al., 2018; Mourad, 2016). Various initiatives aimed at redistributing food have been assessed for their efficiency, by measuring the quantity of saved food (Goossens et al., 2019; Hecht and Neff, 2019). Nonetheless, these evaluations are often unclear regarding whether the food was transferred from retail to organizations that act as stakeholders or from these organizations directly to individuals in need, and they may not consistently account for the food waste generated during the redistribution process. Surprisingly, the amount of food consumed is rarely reported, even though it fundamentally signifies the success of surplus food redistribution (Alexander and Smaje, 2008). There is a need for comprehensive assessments that measure the effectiveness of redistribution strategies in providing nutritional support to vulnerable populations while minimizing waste generation (Cicatiello et al., 2016; Moggi et al., 2018; Reynolds et al., 2015).

Therefore, collecting and redistributing surplus fresh fruits and vegetables, to provide the correct nutritional support to those who require it, necessitates focused and organized interventions, and objective measurement methods. Life Cycle Assessment (LCA) is a structured method used to assess the environmental impact of food supply chains, covering aspects like food production, consumption, and the generation of food waste (Caldeira et al., 2019c).

Most existing studies, as seen in Table 1, have primarily focused on preventing food waste, with relatively less attention placed on alternative food waste management methods like incineration, composting, and anaerobic digestion (Bernstad and la Cour Jansen, 2012; Salemdeeb et al., 2017). Some earlier investigations into food donation have employed a system expansion approach, considering the emissions saved through food donation (Bergström et al., 2020; Damiani et al., 2021; Eriksson et al., 2015). While this approach has revealed notable environmental benefits, the findings can be sensitive to assumptions about the food replacing the donated items, mainly due to limited data availability on the actual types and quantities of the substituted food.

Literature data highlight the need for an additional evaluation, a systematic approach to obtain disaggregated values of food waste, primary research on food waste generation in the EU, quantification discrepancies among studies, underdeveloped evaluation methods for prevention actions, and inconsistent metrics hindering comparisons across food rescue studies. Additionally, limitations within the food donation model, scarcity of research on the effectiveness of food donation, and incomplete assessments of economic, environmental, and social impacts further emphasize the importance of addressing these gaps through enhanced methodologies and additional research efforts to develop more effective strategies for reducing food waste and its environmental consequences.

According to the findings of the literature and the gap identified, this study aims to observe the movement of vegetable products that are given or intercepted by non-profit organizations operating within the Wholesale Fruit and Vegetable Market (called Ortomercato), overseen by SogeMi on behalf of the Municipality of Milan. The Market, largest at the national level, owns 99.9% of the shares and accommodates approximately 110 wholesalers and 97 producers with more than 1,000,000 tonnes of fruits and vegetables marketed every year by wholesalers with retail outlets and export companies present in the market (SogeMi, 2023). These entities, handling 1 million tons of products annually, establish this location as the pulsating core of the city's agri-food system. Some of the brands of the Large Distribution Organization are found here, along with the majority of traders from 93 weekly markets and various ongoing markets throughout the city.

Table 1
Literature papers related to food waste along production and supply chains.

References	Aims	Highlighted limitations
Alexander and Smaje (2008) Riches (2018)	• Analyse food donations for waste minimization and food poverty relief. • Highlight logistical arrangements for retail food waste reduction. • Understand the issues of hunger and food insecurity in food bank nations. • Challenge the effectiveness and moral legitimacy of corporate food banking.	• Frictions in the model affect wider application and control of food flows. • Logistics of perishable items limit extension to smaller retailers. • Lack of attention to historical development and influence of food banking.
Caldeira et al. (2019a)	• Present a high-level top-down approach to food waste accounting. • Support understanding of mass flows in food production and waste.	• Uncertainties in FAO and EUROSTAT data. • Systematic and methodological errors, and model uncertainty. • Data processing errors and conversion from amounts to weight. • Coefficients used are not representative of the EU.
Caldeira et al. (2019b)	• Develop a harmonized modelling system to estimate food waste in EU countries. • Present two modelling approaches to estimate food waste at MS level.	• Discrepancies in food waste quantification due to different approaches. • Lower food waste estimates from waste statistics.
Caldeira et al. (2019c)	• The aim is to identify efficient food waste prevention actions. • The aim includes developing a systematic framework to evaluate prevention actions.	• Lack of appropriate methods to assess the effectiveness of prevention actions. • Need for improvement in data collection and action design.
Goossens et al. (2019)	• Analyse economic costs and benefits of food waste measures. • Identify gaps in evaluation methodologies for food waste prevention measures.	• Lack of complete economic, environmental, and social assessments in evaluations. • Incomplete evaluation of environmental impact elements.
Hecht and Neff (2019)	• Evaluate food rescue interventions to compare effectiveness and methodologies. • Synthesize findings from peer-reviewed studies on food rescue interventions. • Identify promising effects like positive return on investment and decreased environmental burden. • Highlight the need for additional evaluation and recommend a standardized methodology.	• Inconsistent metrics and insufficiently detailed methodology hinder comparison across studies. • Lack of evaluation and dissemination leads to replicating existing approaches.
Sundin et al. (2022)	• Investigate the effectiveness and environmental impact of food donation with rebound effect. • Compare food donation to anaerobic digestion for waste management.	• Rebound effect offset 51% of carbon emissions savings from food donations. • Excluded emissions from re-spending of accrued savings when receiving donated food.

Additionally, numerous catering operators contribute to the vibrant market scene.

Since 2021, a designated space at the Market, aligned with the Food Policy of Milan (named Foody Hub), has facilitated the efforts of volunteer groups and associations to intercept still-edible fruits and vegetables. Thanks to a comprehensive territorial network, these are daily redistributed to the most vulnerable people in Milan's metropolitan area. It is crucial to ensure that families and people in need have balanced and nutritious options, particularly since fruits and vegetables are crucial to a healthy diet. The prioritization of surplus food distribution within the waste hierarchy, as highlighted by the European Commission in the literature review, underscores its pivotal role in sustainable resource management. In this paper, the results of a survey conducted in 2022–2023 at the Foody Hub of the Ortomercato Wholesale Fruit and Vegetable Market in Milan will be presented and discussed. The goal is to quantify the movement of fruit and vegetable products that were given or intercepted by non-profit organizations operating within the Wholesale Fruit and Vegetable Market and assess the environmental impact of these saved items, and proposing an estimate of environmental credits associated with the prevention of food waste, utilizing the LCA tool.

This study contributes to the field of food waste management by offering a comprehensive assessment of the environmental impact of food redistribution. While previous investigations have explored food waste prevention and alternative waste management methods like incineration, composting, and anaerobic digestion, a thorough understanding of food redistribution's environmental benefits remains elusive.

By focusing on Italy's largest wholesale fruit and vegetable market (Ortomercato) and employing a life cycle assessment (LCA), this research quantifies the environmental impact of recovered food products, not only demonstrate the environmental benefits of food redistribution but also providing valuable insights for optimizing operations and establishing an environmental budget within the system.

This approach addresses a critical gap in knowledge, aiming to contribute significantly to the development of more effective food waste reduction strategies for a more sustainable future.

2. Materials and methods

RECUP's primary mission is to recover unsold food that has lost its economic value and restore its social value. An environmental impact assessment was conducted on the activities provided by RECUP APS.

Life Cycle Assessment (LCA) methodology, originating in the 1960s, gained significant traction in environmental science fields since the 1990s. The methodology of Life Cycle Assessment (LCA) offers a standardized approach for quantifying impacts across product life cycles in various industries (de Boer et al., 2014; Goyal et al., 2021). Researchers have applied LCA to assess ecological impacts in food and feed sectors (Smetana et al., 2019; de Boer et al., 2014) and evaluate environmental performance in pharmaceutical production (Ott et al., 2014). Studies highlight LCA's role in designing environmentally sustainable products and processes (Kralisch et al., 2018; Nielsen and Wenzel, 2002; Kralisch and Ott, 2017).

LCA is essential for European and international research projects. The European Commission's PEF and OEF methodologies quantify environmental performance based on LCA principles (European Commission, 2021a, 2021b). These initiatives underscore the significance of LCA in assessing environmental impacts across sectors.

Life Cycle Assessment (LCA) is used in food distribution and food waste management to evaluate the environmental sustainability of the entire life cycle of food products (Denise et al., 2022; Teunis et al., 2018). It provides a comprehensive framework to assess the environmental performance of food systems, including the use of resources, energy consumption, and waste generation (Mónica et al., 2020). LCA can help in identifying opportunities for improvement, such as reducing waste, optimizing processes, and making informed decisions to minimize environmental impacts (Karli et al., 2012). LCA also plays a role in promoting environmentally sustainable practices and raising awareness about the environmental consequences of food waste, leading to more environmentally sustainable habits and processes. The study applied the Life Cycle Assessment (LCA) methodology, considering the complete life cycle of fruits and vegetables recovered from the waste stream and donated as saved food to needy people in Milan's metropolitan area. The LCA methodology was used to quantify the environmental credits and debits generated by this kind of service, adhering to the guidelines outlined in the ISO 14040:2021 and ISO 14044:2021 standards.

2.1. Description of the system analysed

At Ortomercato, RECUP APS prevents food from reaching waste streams as it moves through various wholesalers. Due to inaccuracies in predicting demand, the existence of aesthetic flaws, and the achievement of maturity levels unsuitable for proper management, fruits and vegetables are frequently removed from the Ortomercato's flow, despite they still possess quality attributes that would make them suitable for human consumption. RECUP's operations are integrated into this process capturing fruits and vegetables items that are still suitable for consumption (visiting wholesalers' and retailers' locations) and transporting them to the Foody Hub. Here, with the assistance of both social and industrial volunteers, products are meticulously sorted by edibility. After sorting, products are subsequently made available for donation, while those deemed unsuitable undergo waste management processes such as anaerobic digestion and compost production organized by the third-party affiliate. The fruit and vegetable products that successfully pass the screening process can reach needy people in three different ways: (i) needy people can reach Ortomercato and pick up the product from the Foody Hub, (ii) on the same day, the product can be sent via RECUP's network vehicles to the various Associations, food banks etc. operating in the area around Milan, (ii) the product saved from waste flows can be stored for up to a maximum of 24 h before being collected by the public or (iv) the product can be temporarily stored for up to a maximum of 24 h before being distributed to other Associations that operate in Ortomercato on the day subsequent to RECUP's presence.

2.2. Goal and scope definition

The conducted LCA on the food-saving initiative at Ortomercato was designed to evaluate the environmental impacts associated with the rescue of food from waste streams and its distribution to those in need. This practice could contribute to emissions reduction by preventing and minimizing waste management and the production of new food items.

The objective of this study is to delineate the current practices implemented by the RECUP's weekly activities and evaluate the benefits these activities bring within the Ortomercato context. The LCA study specifically focused on comprehending and quantifying the environmental ramifications of RECUP's operations in Ortomercato over one year, from September 2022 to July 2023. This paper seeks to showcase, through an LCA study, the prospect of reducing the environmental mitigation linked to waste management while simultaneously offering vital support to underprivileged individuals. This consideration is based on the observation that other non-profit Organizations (operate successfully by collecting donations at the Ortomercato. Thus, the primary motivation behind this research is to quantify the movement of fruit and vegetable products that are given or intercepted by non-profit organizations operating within the Wholesale Fruit and Vegetable Market assess the environmental impact of the current scenario, quantifying the positive and negative outcomes of these initiatives by introducing and proposing an environmental credits and debits approach, utilizing the LCA tool.

2.3. Functional unit and reference flow

The concept of a Functional Unit (FU), as defined in ISO 14040:2021 and ISO 14044:2021, is established as the benchmark unit for the system under consideration. As the system under consideration is related more to a service rather than a tangible product, the appropriate functional unit required to assess the environmental impact of the service has been identified. In this context, the functional unit for the system is defined as one year of service within the Ortomercato setting by the RECUP Association, aimed at recovering food products from the waste stream and redistributing them to meet the needs of the indigents. The reference flow was defined as the product (fruit and vegetables) saved from the waste flows at the consumer gate or to an average association operating in the area around Milan.

2.4. System boundaries

The LCA study is a "cradle-to-gate" where "cradle" refers to the production of raw materials, such as fruit and vegetables, and "gate" refers to the point at which the food products recovered from the waste stream are donated to indigents. This system considers all the processes related to Ortomercato's internal and external logistics, as well as the food waste streams resulting from the selection phase of the saved food.

In particular, as depicted in Fig. 2, the details of the analysed flows can be divided into four phases:

Upstream processes (1) which include.

- Production of fruit and vegetables.
- Production of packaging for the product.
- Transport of packaged products to wholesalers.
- Ortomercato internal transport to the Foody Hub by Third Sector Organization, collecting surplus fruit and vegetables.

Core processes (2) at Foody Hub which include.

- Fruit and vegetable sorting.
- Quantification and classification of sorted fruits and vegetables.

Waste management processes (3) which include.

- Transport of waste produced to the waste management site.
- Treatment of waste produced.

Distribution processes (4) which include.

- Storage of saved products.
- Fruit and vegetable distribution.

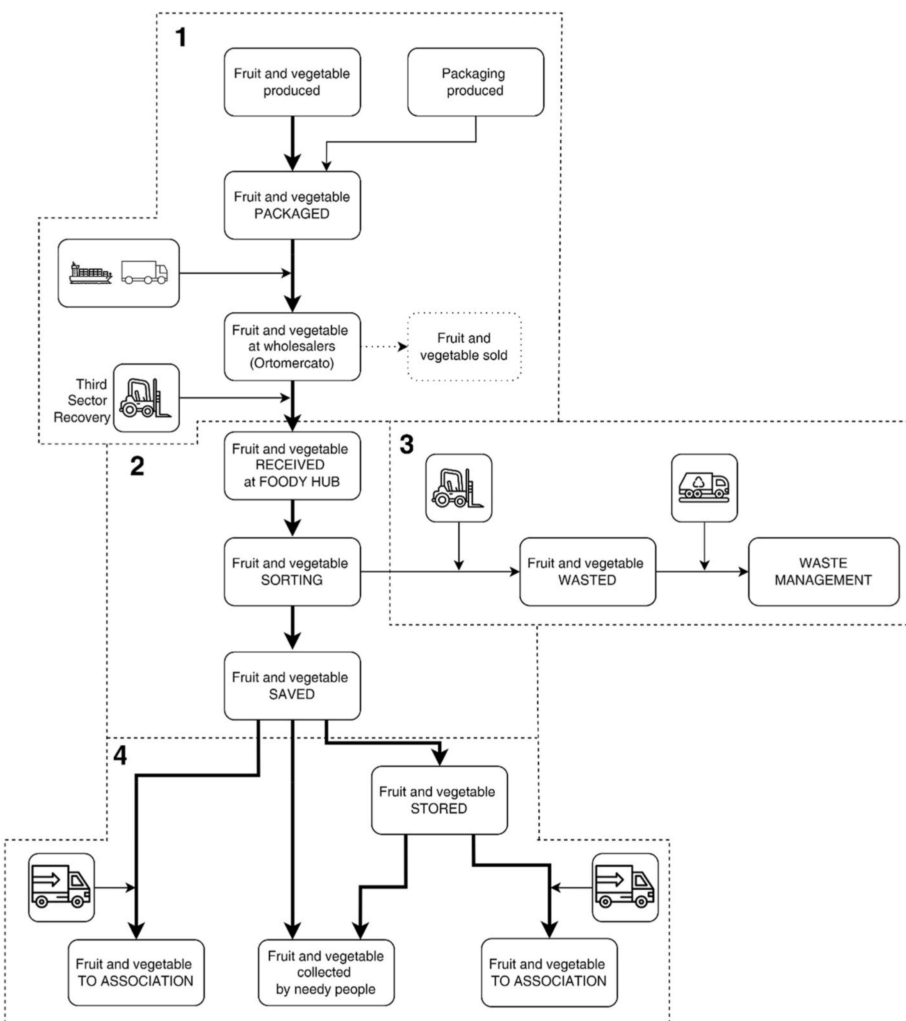


Fig. 2. Description of the system analysed and subdivision of the product flow into the 4 phases of Upstream, Core waste and distribution processes, dividing the latter into waste management. The fruit and vegetables are moved in transport packaging.

2.5. Life cycle inventory modelling framework

2.5.1. Allocation method

The LCA study required allocation procedures for production, distribution, waste management, and storage at different points in the system. Upon donation, the product loses its original economic value related to its commercial life. In the present study, mass allocation criteria were employed to assign fair values to each food product having a charitable purpose.

2.5.2. Temporal and geographical representativeness

The study refers to a temporal representativeness of one year, set in a year of activity from September 2022 to July 2023. Geographical representativeness is limited to the national context, specifically to the Lombardy region, the region within which the RECUP activity was analysed in detail.

2.6. Limitations of the study

Limitations of this study may be related to geographical and temporal representativeness. Considerations can only be made about the case study analysed and the availability of the information collected. About the information on the origin of the food products, some of this information could not be collected and, as a precaution, an average global transport was attributed to these products.

3. Life cycle inventory (LCI)

The assessment of the food donation scenario involved the analysis of several aspects, including food products, modes of transport, types of packaging, electricity consumption and waste management scenarios. A detailed description of all these factors is provided in the following sections.

3.1. Type of food products

A survey was used to collect data on various aspects of the products received at the Foody Hub, including the type of product received, the number of donated items, the quantity of fruit and vegetables saved, and the quantity discarded by RECUP APS following visual sorting due to its unsuitability for human consumption (details of products mass flows are reported in supplementary data SD1).

Information on the origin of each reference food item was collected to calculate the emissions linked to the production of fruits and vegetables intercepted by RECUP's volunteers before expiration from wholesalers and/or retailers. The Ecoinvent 3.8 database was used to support the inventory phase.

Two different types of relative datasets were extracted from this database, which differ in the inclusion of transport according to the origin of the product. Fruit and vegetable production datasets may or may not include transport information, depending on the data collected by RECUP APS at the Foody Hub and the availability of the dataset in the database. As a selection criterion, datasets were chosen if they could meet the criteria of geographical representativeness of the food produced. Specifically, datasets were selected that reflected production in the same reference country. If the origin was not specified or not available in the database, market-related datasets were used, representing an average value, and including an average representation of transport from the specific region.

3.2. Food packaging

Packaging received with donated food at the Foody Hub was classified in terms of quantity and material. The study revealed that 70% of the packaging was made of rigid polypropylene plastic boxes, 20% was made from wood crates, and the remaining 10% was characterized by corrugated cardboard boxes. The various types of packaging were classified and characterized, and the average capacity for each box passing through the Foody Hub was determined. Consequently, the average dimension, weight, load capacity, and kg of packaging per kg of fruit of the most frequently used packaging were documented and reported in Table 2.

Regarding the waste treatment of the different packaging solutions used in this scenario, wood crates are directed to recycling systems while plastic and cardboard boxes are integrated into the national waste management scenario including an average transport of 50 km from the Foody Hub to the waste management plant.

3.3. Transport of food products from origin to ortomercato

Data related to upstream transportation were obtained via a survey. The various products were sourced from all locations worldwide. The survey considered the following transport-related data as representative of all food donations: (i) product origin and (ii) typical mode of transportation for fruits and vegetables. According to the obtained data, the Eco-Transit platform was used to determine the distance between the origin and the Ortomercato (located at Via Cesare Lombroso, 54, 20137, Milan, Italy). The average distances from the countries of origin of the vegetable products intercepted and collected at Ortomercato market were measured and the average mode of transport proposed by the Eco-Transit platform was identified and classified. Details are given in Table 3. For each mode of transport, the corresponding emissions were calculated, taking into account the use of refrigerated transport by truck and ship.

3.4. Internal logistics at ortomercato

The transportation of food products from wholesalers to RECUP and the disposal of waste products from the Foody Hub to the waste collection site were facilitated using forklifts. Analysing the scenario and using a survey, several factors were considered including a minimum load requirement per trip when transporting the donated product from the wholesaler to the Foody Hub. In this analysis, the following forklift factors were considered.

- maximum allowable speed forklifts within Ortomercato: 9 km/h;
- average distance covered from a general wholesaler to the Foody Hub: 500 m;
- energy consumption: 1 kWh/h;
- maximum weight limit per trip from the wholesaler to the Foody Hub: 100 kg.

Concerning the transportation of waste from the Foody Hub to the waste collection point, the maximum load considered per trip was

Table 2
Average of dimension, weight, load capacity, and kg of packaging per kg of fruit and vegetable related to the most frequent packaging received at the Foody Hub.

Crate type	Material used	Dimension (cm)	Weight (kg)	Load capacity (kg)	$\frac{kg\ packaging}{kg\ product}$
Wood	**Wood**	30 × 50 × 14	0.57	7	0.08
Plastic	**Polypropylene**	30 × 50 × 16	0.46	7	0.07
Cardboard	**Cardboard**	30 × 50 × 15	0.42	7	0.06

Table 3
Modes of Transportation and Average Distances (in kilometres) from the Regions of Origin for Fruit and Vegetables intercepted and collected by RECUP APS.

Transport mode	Unit of measure	Italy	Europe	Asia	Africa	Australia	North America	South America
Road	km	500	1000	1865	3501	1480	1150	1983
Sea	km	–	–	17150	8415	16607	10370	9956
Total	km	500	1000	19015	11916	18087	11520	11939

determined to be 2000 kg (equivalent to one trip per day). The forklift for internal handling involves electricity consumption.

3.5. Food waste treatment

Since donated food may not always be in optimal condition, the products undergoing screening at the Foody Hub by RECUP are divided into two separate streams: items that pass the screening are saved and donated to indigents, while items that do not pass due to physical and mechanical characteristics rendering them unsuitable for human consumption are redirected to the waste stream. These products are collected in bins and transported via forklifts to the designated collection area within Ortomercato.

Subsequently, they are directed towards their designated waste streams, utilizing waste collection trucks and subjected to appropriate treatments determined by their nature. Organic material will be processed to generate biogas and compost (allocated in 50%/50%).

3.6. Food storage

Considering the flows of food recovered by RECUP throughout the activity, an average of 10% of the overall products have been recognized as products stored in the chilled compartment for a maximum of 24 h. This quantity refers to the food that cannot be screened on the same day due to high quantities. The power required to preserve food products at temperatures of +1/-1 °C is equal to 35 W/m^3. The volume occupation of 1 ton is related to 10.8 m^3 (2 × 2x2.7 m). Considering the power and the time of usage of the refrigeration machine (24 h), the efficiency factor (0.7) and the compressor run time (1/3 of the usage time), a total of 3.9 kWh can be attributed to 1 ton of food product stored in the cellar. The electricity consumption for chilling food, typically exceeding a pallet and weighing more than 750 kg is considered.

3.7. Transport of food saved from Foody Hub to a general association

Regarding transport in the downstream stages, a survey was used to determine the average distance travelled for the distribution of the product from the Ortomercato market to a generic social organization operating within the stakeholder network, committed to redistributing food across the Metropolitan City of Milan. The average distance was quantified at 25 km. The vehicle used for this type of transport is a light commercial vehicle.

Table 4
Impact categories, relative units, and corresponding acronyms used within the study, based on EF 3.0.

Impact category	Acronyms	Unit of measure
Climate change	CC	kg CO_2 eq
Ozone depletion	OD	kg CFC11 eq
Ionizing radiation	IR	kBq U-235 eq
Photochemical ozone formation	POF	kg NMVOC eq
Particulate matter	PM	disease inc.
Human toxicity, non-cancer	HT-NC	CTUh
Human toxicity, cancer	HT-C	CTUh
Acidification	ACID	mol H+ eq
Eutrophication, freshwater	EU-F	kg P eq
Eutrophication, marine	EU-M	kg N eq
Eutrophication, terrestrial	EU-T	mol N eq
Ecotoxicity, freshwater	ECOTOX	CTUe
Land use	LU	Pt
Water use	WU	m^3 depriv.
Resource use, fossils	RU-F	MJ
Resource use, minerals, and metals	RU-M	kg Sb eq

4. Life cycle impact assessment (LCIA)

In line with the study's objective, the LCA results are proposed using the EF 3.0 impact assessment method developed by the European Commission (European Commission, 2021a, 2021b).

To study the environmental impact, SimaPro software version 9.5. (PRé Sustainability, Amersfoort, The Netherlands) and the Eco-invent v 3.8 database were used, following cut-off allocation criteria.

The LCIA phase requests to assess potential environmental impacts by analysing life cycle inventory data. It involves linking inventory data on pollutants to specific categories of environmental impact. Please refer to Table 4 for a summary of impact categories, relative units, and corresponding acronyms.

5. Results and discussions

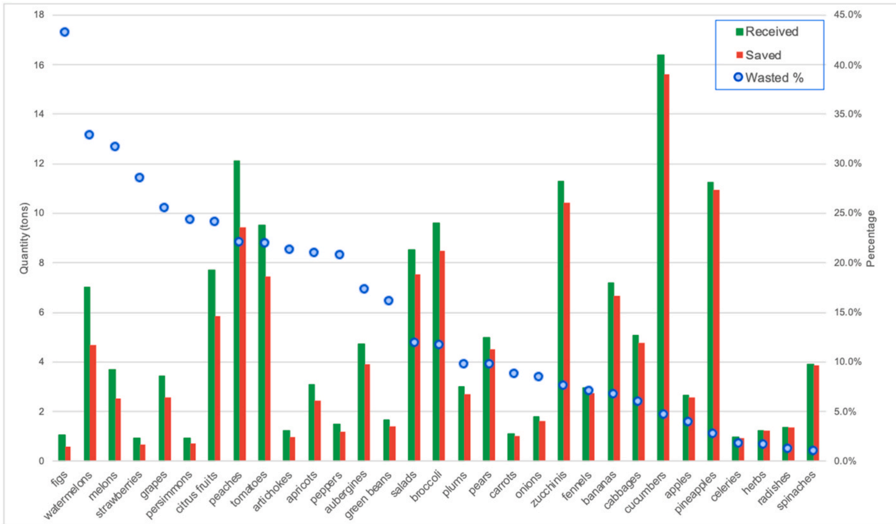
To better present the various findings of the analysis, the results are divided into two separate sections: the first proposes a quantitative analysis, while the second analyses relate to the corresponding environmental impacts.

5.1. Quantitative results

The survey used to collect data on the flow of fruit and vegetables through the RECUP screening process was carefully designed to estimate the inflow and outflow of the system. During the analysed period, the RECUP organization worked for a cumulative total of 49 working days (once a week, excluding holidays) gathering a total of 61 references, and providing 1527 responses to the survey. From the results it emerged that it was successfully collected a significant quantity of fruit and vegetables, amounting to 157.86 tons (0.0002% of the fruit and vegetables marketed in the Ortomercato according to SogeMi (2023). RECUP managed to save 136.84 tons of fruits and vegetables that would otherwise have been wasted (saving 86.7 % of the intercepted products). However, 21 tons of food were ultimately wasted due to screening measures. Legumes and nuts, as well as mushrooms and cereals, represented less than 5% of the input product, and for this reason, their data were not included in the analysis.

The weight of food recovered by RECUP during the 49 working days within the Ortomercato is illustrated in Fig. 3. The provided quantities account for three distinct types of flows: received products, saved (collected/donated) products, and wasted products (those directed to the disposal flow after screening). The figure represents only the first 30 items, nevertheless representing the 96% of the total collected.

Cucumbers account for the largest quantity of food items received (16.4 tons), followed by peaches (12.1 tons) and zucchinis (11.3 tons). Pineapples and broccoli hold the fourth and fifth positions, with 11.2 and 9.6 tons each, respectively. The analysing of the outbound flows from the Foody Hub reveals that peaches, despite ranking as the second most donated product, represent the most rejected item, with about 2.7 tons, corresponding to almost 21% of the total collected amount. On the other hand, the other frequently wasted products in terms of incoming



Top 5 Items	Received (tons)
cucumbers	16.4
peaches	12.1
zucchinis	11.3
pineapples	11.2
broccoli	9.6

Top 5 Items	Wasted (tons)
peaches	2.7
watermelons	2.3
tomatoes	2.1
citrus fruits	1.9
melons	1.2

Fig. 3. The most significant items (96% of the total) in terms of quantity (tons) related to the received, saved and wasted products after the screening carried out by the charity organisation at the Foody Hub area Ortomercato within the period September ‘22 – July ‘23. The top received and wasted items are also represented.

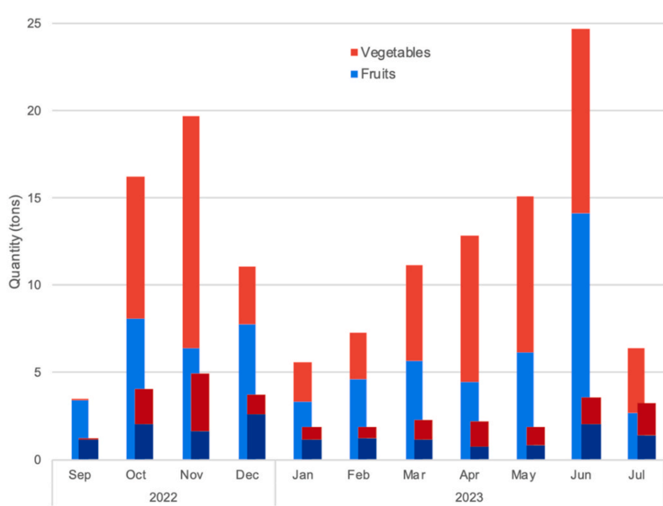


Fig. 4. Quantity (tons) of received items of fruits and vegetables distributed by month. In darker colours, the specific quantity per day of activity. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

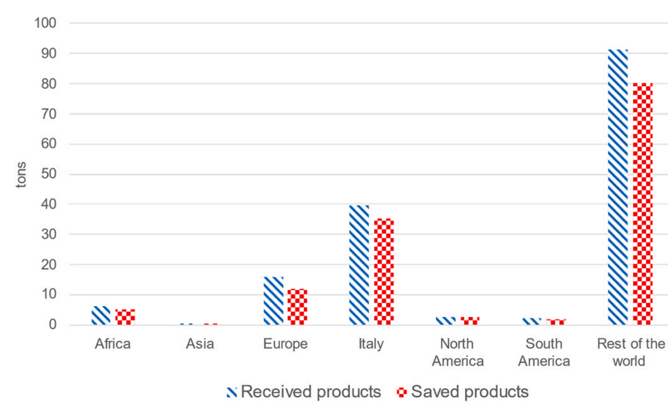


Fig. 5. Origin of the food products donated by wholesalers to the charity organization within the period September ‘22 – July ‘23. The term “Rest of the world” has been used in case of impossible traceability.

quantity (watermelon, tomatoes, citrus fruits and melons) do not belong to the category of the most received items. Notably, watermelons, and melons registered the highest wasted rates, surpassing 30% when calculated as a percentage relative to the donated quantity.

Furthermore, the inventory data were analysed to assess the seasonal variation in the donated items, divided for fruits and vegetables. Fig. 4 illustrates the results of this analysis, providing insight into the monthly inflow of the food items to the Foody Hub. Additionally, the figure presents the quantity of donated items per day of harvest for each month.

October, November, and June emerged as the months during which the organization collected the highest amounts of products. As regards to fruits, an increase in the collection of products was evident in June (12.1 tons), whereas January recorded the least amount of collected products at 3.4 tons. A comparable monthly distribution pattern was observed for vegetables, with minimal amounts harvested in January and February (2.2 and 2.6 tons, respectively). From March to June, an increase trend was observed, and a peak was evident in November, with a maximum value of 13.3 tons. September recorded almost negligible quantity of vegetables received.

By factoring in the number of days during which RECUP was involved in activities at Ortomercato for each month, the average quantity collected per day of activity was also computed. The findings highlight that the autumn season proved the most useful period for collecting food products intended to be donated to indigents. Specifically, in both October and November, each day of activity yielded around 4–5 tons of fresh food.

The collected survey was also organized to provide information on the origin of the products collected by RECUP APS. However, as depicted in Fig. 5, for certain products, the info related to traceability was missing. For these products, an average transport value representative of world distribution has been entered.

The majority of the traced food items were sourced from Italy, whereas the untraced food items, estimated at around 91 tons, were categorized under GLO (global), followed by the European Union region, Africa, north and South America, and Asia for the chosen study period. The data indicates that the lowest food donation comes from the Asian region, where only 27.7 kgs of food were donated. This suggests that the products of Asian origin are less commonly donated by the wholesalers at the Ortomercato. This could be due to the lower quantity of fruit and vegetables imported from the Asian continent, resulting in fewer surpluses at the distribution level.

5.2. Environmental impact assessment

In the environmental assessment of the food collection and rescue activities within the Foody Hub, the emissions related to the inputs and outputs of the system were calculated using the Environmental Footprint 3.0 methodology. In a holistic approach, impact categories beyond climate change are of paramount importance to avoid unintended burden shifting to other environmental impact categories, therefore the following sections reflect on the different impact characteristics.

5.2.1. Environmental characterization of product intercepted from wastage (upstream processes – 1)

The incoming product flow is characterised by the product, packaging, and transport to reach the wholesale market and subsequently the Foody Hub. Fig. 2 (in section 2.4) shows the process and product flows involved in receiving the product at the Foody Hub, and Fig. 6 shows the percentage contribution of each of these factors to each impact indicator.

The analysis unequivocally demonstrates that food production is the predominant factor influencing almost all impact categories, constituting an average percentage of 63%. Transportation of food is the second largest impact factor, with an average impact value across impact categories of 26.9%. In some impact categories, such as ozone depletion and ionizing radiation, this factor exceeds 50%. When packaging is included in the analysis, this factor represents an average value above 10% among the impact categories. Internal transport by forklift can be considered negligible due to a percentage value lower than 1% in each impact category.

Given that the most impactful factor is the food product, a detailed analysis was carried out to understand which vegetable item collected by RECUP had a greater impact compared to the total recovered. This analysis has led to the identification of various food products with high environmental impact, as proposed in Fig. 7, a grouping by fruit and vegetable class is visible where the vegetable class stands out more than

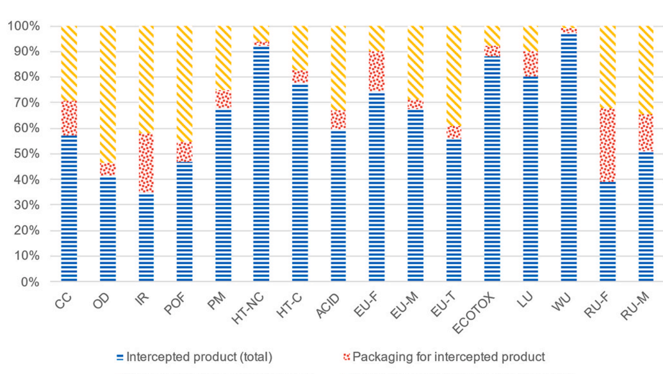


Fig. 6. Environmental impacts of products and activities involved in the upstream processes. CC: Climate Change; OD: Ozone Depletion; IR: Ionizing Radiation; POF: Photochemical Ozone Formation; PM: Particulate Matter; HT-NC: Human Toxicity, Non-Cancer; HT-C: Human Toxicity, Cancer; ACID: Acidification; EU-F: Eutrophication, Freshwater; EU-M: Eutrophication, Marine; EU-T: Eutrophication, Terrestrial; ECOTOX: Ecotoxicity, Freshwater; LU: Land Use; WU: Water Use; RU-F: Resource Use, Fossils; RU-M: Resource Use, Minerals and Metals.

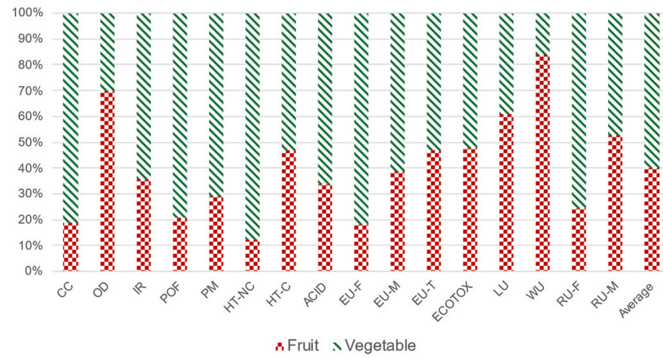


Fig. 7. Environmental impacts of inlet fruit and vegetable products. CC: Climate Change; OD: Ozone Depletion; IR: Ionizing Radiation; POF: Photochemical Ozone Formation; PM: Particulate Matter; HT-NC: Human Toxicity, Non-Cancer; HT-C: Human Toxicity, Cancer; ACID: Acidification; EU-F: Eutrophication, Freshwater; EU-M: Eutrophication, Marine; EU-T: Eutrophication, Terrestrial; ECOTOX: Ecotoxicity, Freshwater; LU: Land Use; WU: Water Use; RU-F: Resource Use, Fossils; RU-M: Resource Use, Minerals and Metals.

fruit, specifically, as reported in supplementary data tables (SD2) cucumbers have a responsibility value average of 24% across impact categories, followed by peaches (7%), peppers (6%), artichokes (6%) and tomatoes (5%).

5.2.2. Environmental characterization of saved product (core processes – 2)

Considering RECUP volunteers' goal to prevent food waste, sort items, and preserve them for disadvantaged individuals, it is crucial to examine the distribution of saved products following the screening phase.

The quantification and characterisation of the environmental impact of the sorting and preservation process for the vegetable items is of utmost importance. As represented in Figs. 5 and 6, the analysis of the saved products indicates a close resemblance to the environmental impact results obtained in the upstream phase. Transportation of fresh produce emerges as the second most significant factor, with an average impact value of 27.3% across impact categories, while packaging consistently contributes to less than 10%.

Fig. 8 gives a complete overview of the environmental impact percentages of the different food products in the different categories, referring only to the food products saved. From Fig. 9 it is possible to

Fig. 8. Environmental impacts characterization of products and activities involved in the Core processes. CC: Climate Change; OD: Ozone Depletion; IR: Ionizing Radiation; POF: Photochemical Ozone Formation; PM: Particulate Matter; HT-NC: Human Toxicity, Non-Cancer; HT-C: Human Toxicity, Cancer; ACID: Acidification; EU-F: Eutrophication, Freshwater; EU-M: Eutrophication, Marine; EU-T: Eutrophication, Terrestrial; ECOTOX: Ecotoxicity, Freshwater; LU: Land Use; WU: Water Use; RU-F: Resource Use, Fossils; RU-M: Resource Use, Minerals and Metals.

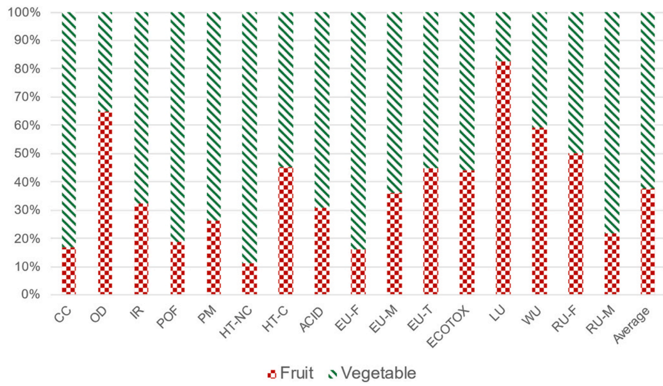


Fig. 9. Environmental impacts characterization of saved food items. CC: Climate Change; OD: Ozone Depletion; IR: Ionizing Radiation; POF: Photochemical Ozone Formation; PM: Particulate Matter; HT-NC: Human Toxicity, Non-Cancer; HT-C: Human Toxicity, Cancer; ACID: Acidification; EU-F: Eutrophication, Freshwater; EU-M: Eutrophication, Marine; EU-T: Eutrophication, Terrestrial; ECOTOX: Ecotoxicity, Freshwater; LU: Land Use; WU: Water Use; RU-F: Resource Use, Fossils; RU-M: Resource Use, Minerals and Metals.

make some key observations and discussions, such as specific observations on the product type that contribute most to the environmental impact, vegetables represent the highest contributor to the environmental impact quantification. As reported in supplementary data table SD3 cucumbers present high percentages in different impact categories, underlining their significant environmental footprint, strongly linked to the amount of product saved from the flow some waste. Fruits such as peaches and apricots show significant impacts in the freshwater eutrophication (EU-F) and marine eutrophication (EU-M) categories. The production and distribution of peppers and tomatoes, on the other hand, contribute significantly to Climate Change (CC) and Human Toxicity – Cancer (HT-C). Generic fruits have a relatively high impact in the Ozone Depletion (OD) category. The group of products that individually have an average impact of less than 1% collectively contribute less to the environmental impact, indicating that these items have a relatively small environmental footprint.

5.2.3. *Environmental characterization of wasted product (waste processes – 3)*

For products identified as waste after the screening phase, the quantification of their environmental impact involves different steps

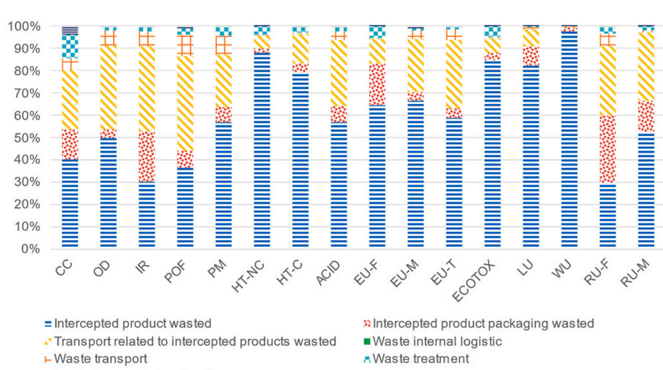


Fig. 10. Environmental impacts of products and activities involved in the waste management processes. CC: Climate Change; OD: Ozone Depletion; IR: Ionizing Radiation; POF: Photochemical Ozone Formation; PM: Particulate Matter; HT-NC: Human Toxicity, Non-Cancer; HT-C: Human Toxicity, Cancer; ACID: Acidification; EU-F: Eutrophication, Freshwater; EU-M: Eutrophication, Marine; EU-T: Eutrophication, Terrestrial; ECOTOX: Ecotoxicity, Freshwater; LU: Land Use; WU: Water Use; RU-F: Resource Use, Fossils; RU-M: Resource Use, Minerals and Metals.

depending on the nature of the product. As reported in Fig. 10, these include transport from the Foody Hub to the waste collection point, loading onto waste trucks, average transport from the nursery to the waste disposal site and waste treatment. In addition, contributions from wasteful phases in production, packaging and transport in the upstream phase should also be considered.

Analysis of the results shows that the largest contribution to waste streams is associated with the discarded food product, with an average impact value of 34% across the different impact categories. The production of product packaging is the second largest contributor with an average impact value of 17%, while transport ranks third with a value of 11%.

The waste transport and intercepted product waste treatment, although limited, has a significant impact, particularly in the Climate Change category, where it contributes 20% overall and 6% on average across impact categories. The packaging waste treatment and the transport of waste by lorry together account for more than 15% in the climate change impact category.

With regard to the environmental impact contribution mainly from discarded vegetables, the Supplementary data table SD1 suggests a classification of the vegetable items with the highest weight for each impact category. In particular, cucumbers, cauliflowers, peaches, and strawberries emerge as some of the most impactful products in this context.

5.2.4. *Environmental characterization of distribution of the product (downstream processes – 4)*

Once a food product has been recovered from the waste stream, it can follow various routes, including the possibility of refrigerated storage and commercial wheel transport, as described in the Materials and Methods section. The results presented in Table 5 show that the contribution of the preservation phase is minimal, not exceeding 1% of this phase. In contrast, for the transport phase, this factor accounts for 99% of the contribution of the distribution processes in section 5.2.

This suggests that, in the context of the EIA, the conservation phase has a negligible impact, while the transport phase plays a dominant role in the contribution to downstream processes. Grasping the significance of these percentages enables informed decision-making and strategy formulation concerning the preservation and transportation of rescued food. It underscores the necessity to focus on and enhance the efficiency of the transportation element to reduce the overall environmental impact.

These findings highlight the importance of addressing the environmental impacts associated with the disposal of food products and point to specific areas, such as transport and treatment systems, where targeted sustainability and waste reduction efforts could be particularly beneficial. The classification of high-impact food products provides valuable information for prioritising actions and optimizing waste management.

5.3. *Environmental balance*

The Foody Hub, located within the Ortomercato market, serves the crucial function of rescuing food destined for landfill, thanks to the coordinated efforts of volunteers from the Third Sector. The primary role of the activities involves screening and identifying fruit and vegetable products suitable for rescue and distribution to those in need. This operation not only allows to recovery of edible food products but also avoids the production of new products, consequently reducing additional emissions into the environment and the associated environmental costs of production.

The concept of environmental impact avoidance was applied to this study, this approach is derived from "carbon avoidance" which refers to the practice of reducing or avoiding the emission of greenhouse gases to mitigate climate change and limit the negative impact on the environment by adopting environmentally sustainable practices or lifestyles

Table 5
Environmental impact per FU related to the different phases of the product life cycle.

Impact category	Unit of measure per FU	Intercepted product	Packaging	Transport	Internal logistics	Intercepted product wasted	Intercepted product packaging wasted	Transport related to waste	Waste internal logistic	Waste transport	Waste treatment	Packaging waste treatment	Storage at the Foody Hub	Transport from the Foody Hub to the needy people
CC	**kg CO2 eq**	$1.17 \times 10^{+05}$	$2.76 \times 10^{+04}$	$5.97 \times 10^{+04}$	$1.86 \times 10^{+01}$	$5.21 \times 10^{+04}$	$8.22 \times 10^{+01}$	$7.03 \times 10^{+03}$	$1.13 \times 10^{+04}$	$3.77 \times 10^{+03}$	$7.62 \times 10^{+03}$	2.64	$1.06 \times 10^{+05}$	$2.39 \times 10^{+04}$
OD	**kg CFC11 eq**	1.05×10^{-02}	1.25×10^{-03}	1.34×10^{-02}	2.53×10^{-06}	1.17×10^{-02}	1.76×10^{-06}	1.44×10^{-04}	2.27×10^{-03}	1.70×10^{-04}	1.72×10^{-03}	3.59×10^{-07}	8.18×10^{-03}	1.08×10^{-03}
IR	**kBq U-235 eq**	$3.06 \times 10^{+03}$	$2.03 \times 10^{+03}$	$3.70 \times 10^{+03}$	2.55	$3.22 \times 10^{+03}$	$1.02 \times 10^{+01}$	$2.80 \times 10^{+02}$	$3.78 \times 10^{+02}$	$2.78 \times 10^{+02}$	$4.73 \times 10^{+02}$	3.62×10^{-01}	$2.68 \times 10^{+03}$	$1.76 \times 10^{+03}$
POF	**kg NMVOC eq**	$5.26 \times 10^{+02}$	$8.61 \times 10^{+01}$	$5.09 \times 10^{+02}$	4.02×10^{-02}	$4.46 \times 10^{+02}$	2.37×10^{-01}	$4.55 \times 10^{+01}$	$5.36 \times 10^{+01}$	$1.18 \times 10^{+01}$	$6.30 \times 10^{+01}$	5.71×10^{-03}	$4.72 \times 10^{+02}$	$7.44 \times 10^{+01}$
PM	**disease inc.**	1.06×10^{-02}	1.11×10^{-03}	3.92×10^{-03}	3.23×10^{-07}	3.41×10^{-03}	1.35×10^{-06}	6.85×10^{-04}	1.25×10^{-03}	1.51×10^{-04}	5.07×10^{-04}	4.58×10^{-08}	9.34×10^{-03}	9.56×10^{-04}
HT-NC	**CTUh**	1.09×10^{-02}	2.16×10^{-04}	7.29×10^{-04}	1.06×10^{-07}	6.35×10^{-04}	5.00×10^{-07}	1.32×10^{-04}	1.48×10^{-03}	2.95×10^{-05}	9.33×10^{-05}	1.50×10^{-08}	9.44×10^{-03}	1.87×10^{-04}
HT-C	**CTUh**	1.44×10^{-04}	9.10×10^{-06}	3.19×10^{-05}	4.15×10^{-09}	2.78×10^{-05}	2.10×10^{-08}	1.04×10^{-05}	2.44×10^{-05}	1.24×10^{-06}	4.07×10^{-06}	5.90×10^{-10}	1.19×10^{-04}	7.86×10^{-06}
ACID	**mol H+ eq**	$9.51 \times 10^{+02}$	$1.18 \times 10^{+02}$	$5.27 \times 10^{+02}$	8.45×10^{-02}	$4.62 \times 10^{+02}$	2.85×10^{-01}	$3.20 \times 10^{+01}$	$1.26 \times 10^{+02}$	$1.61 \times 10^{+01}$	$6.49 \times 10^{+01}$	1.20×10^{-02}	$8.24 \times 10^{+02}$	$1.02 \times 10^{+02}$
EU-F	**kg P eq**	$3.45 \times 10^{+01}$	7.24	4.53	4.23×10^{-03}	3.95	1.25×10^{-02}	9.16×10^{-01}	3.42	9.88×10^{-01}	5.82×10^{-01}	6.01×10^{-04}	$3.11 \times 10^{+01}$	6.25
EU-M	**kg N eq**	$4.03 \times 10^{+02}$	$2.39 \times 10^{+01}$	$1.72 \times 10^{+02}$	1.29×10^{-02}	$1.51 \times 10^{+02}$	4.86×10^{-02}	$1.08 \times 10^{+01}$	$5.87 \times 10^{+01}$	3.27	$2.13 \times 10^{+01}$	1.83×10^{-03}	$3.44 \times 10^{+02}$	$2.07 \times 10^{+01}$
EU-T	**mol N eq**	$2.68 \times 10^{+03}$	$2.38 \times 10^{+02}$	$1.88 \times 10^{+03}$	1.43×10^{-01}	$1.65 \times 10^{+03}$	5.52×10^{-01}	$1.16 \times 10^{+02}$	$4.45 \times 10^{+02}$	$3.26 \times 10^{+01}$	$2.32 \times 10^{+02}$	2.04×10^{-02}	$2.24 \times 10^{+03}$	$2.06 \times 10^{+02}$
ECOTOX	**CTUe**	$7.95 \times 10^{+06}$	$3.50 \times 10^{+05}$	$7.22 \times 10^{+05}$	$1.77 \times 10^{+02}$	$6.30 \times 10^{+05}$	$1.51 \times 10^{+02}$	$4.70 \times 10^{+04}$	$1.17 \times 10^{+06}$	$4.77 \times 10^{+04}$	$9.25 \times 10^{+04}$	$2.52 \times 10^{+01}$	$6.77 \times 10^{+06}$	$3.02 \times 10^{+05}$
LU	**Pt**	$3.11 \times 10^{+06}$	$3.81 \times 10^{+05}$	$3.83 \times 10^{+05}$	$5.19 \times 10^{+01}$	$3.33 \times 10^{+05}$	$2.03 \times 10^{+02}$	$3.96 \times 10^{+04}$	$5.07 \times 10^{+05}$	$5.20 \times 10^{+04}$	$4.97 \times 10^{+04}$	7.37	$2.60 \times 10^{+06}$	$3.29 \times 10^{+05}$
WU	**m3 depriv.**	$4.48 \times 10^{+05}$	$1.02 \times 10^{+04}$	$2.90 \times 10^{+03}$	$1.24 \times 10^{+01}$	$2.53 \times 10^{+03}$	$4.97 \times 10^{+01}$	$4.70 \times 10^{+02}$	$8.04 \times 10^{+04}$	$1.40 \times 10^{+03}$	$3.73 \times 10^{+02}$	1.75	$3.68 \times 10^{+05}$	$8.84 \times 10^{+03}$
RU-F	**MJ**	$9.61 \times 10^{+05}$	$7.11 \times 10^{+05}$	$7.98 \times 10^{+05}$	$2.81 \times 10^{+02}$	$6.96 \times 10^{+05}$	$1.24 \times 10^{+03}$	$9.63 \times 10^{+04}$	$9.74 \times 10^{+04}$	$9.70 \times 10^{+04}$	$1.02 \times 10^{+05}$	$3.99 \times 10^{+01}$	$8.63 \times 10^{+05}$	$6.14 \times 10^{+05}$
RU-M	**kg Sb eq**	4.45×10^{-01}	1.28×10^{-01}	3.02×10^{-01}	4.01×10^{-05}	2.64×10^{-01}	1.40×10^{-04}	5.58×10^{-02}	6.66×10^{-02}	1.75×10^{-02}	3.86×10^{-02}	5.70×10^{-06}	3.79×10^{-01}	1.11×10^{-01}

that generate less carbon emissions (Acampora et al., 2023; Spilker and Nugent, 2022). This concept has allowed us to introduce an important aspect of this work, namely the evaluation of the environmental balance by combining the concept of carbon reduction with all impact categories.

These socially beneficial endeavours can be seen as generating environmental credits since they conserve both energy consumption and products approaching the end of their life. This, in turn, obviates the necessity of procuring new products (Al-Obadi et al., 2022).

By analysing the life cycle phases of products passing through the Foody Hub, it is possible to identify positive and negative values depending on the nature and destination of each item.

The term “amount saved” specifically refers to the fresh produce rescued and spared, earning environmental credits for its significant contribution to waste reduction. Conversely, “inputs” such as transport, storage, and waste streams are associated with a debit, reflecting the environmental costs associated with food production, transportation, and disposal. Apart from the production phase, the creation of waste (“amount of waste”) results in an environmental burden, considering the environmental consequences of unconsumed food and the emissions generated by transportation and disposal systems.

To better highlight the positive and negative factors that affect the system analysed, the following equation was used to calculate the results.

$$EIB = -\ EI\ Upstream\ processes + EI\ Waste\ processes + EI\ Distribution\ processes$$

where.

EIB: Environmental Impact Balance
EI: Environmental Impact

To avoid double counting, the environmental impact (EI) associated with the core process has been excluded from the formula. From the potential environmental benefit identified in the EI Upstream Processes, all costs associated with the management of the saved product and the generation of waste have been added.

The result of the Environmental Impact Balance is negative representing a reduction in emissions achieved by avoiding waste through interception of fresh produce surpluses, collection, and sorting within the Foody Hub. The results depicted in Fig. 11 are offered in graphical and percentage formats, presenting the comprehensive environmental balance that includes all the factors examined thus far. It is crucial to note that the environmental benefit extends beyond the simple preservation and disposal of products categorized as waste. As of at the end of the analysed year, the overall balance is negative, signifying the generation of environmental credits. To better understand the different factors influencing the Environmental Impact Balance and their weight, Table 6 shows the numerical values used to develop Fig. 11.

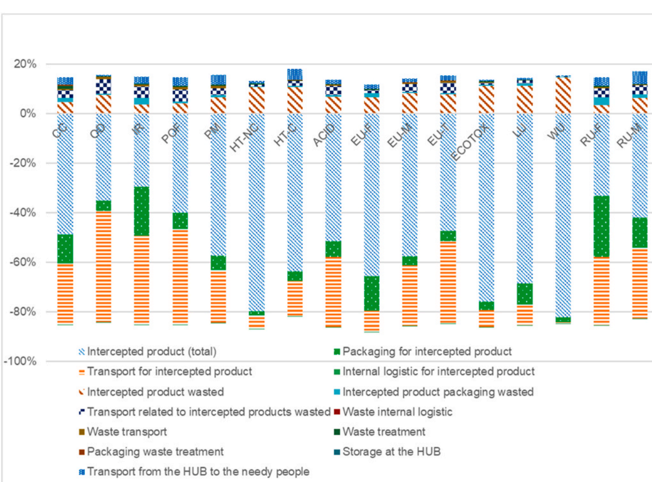


Fig. 11. Environmental balance related to debits and credits net balance and to the specific step involved in the analysis. CC: Climate Change; OD: Ozone Depletion; IR: Ionizing Radiation; POF: Photochemical Ozone Formation; PM: Particulate Matter; HT-NC: Human Toxicity, Non-Cancer; HT-C: Human Toxicity, Cancer; ACID: Acidification; EU-F: Eutrophication, Freshwater; EU-M: Eutrophication, Marine; EU-T: Eutrophication, Terrestrial; ECOTOX: Ecotoxicity, Freshwater; LU: Land Use; WU: Water Use; RU-F: Resource Use, Fossils; RU-M: Resource Use, Minerals and Metals.

Each phase of the product life cycle has been classified as belonging to the class of environmental credits or debits.

This table gives a detailed overview of the environmental impacts associated with various fresh produce, broken down into the different impact categories. First of all, there are two main categories of values reported in the table: “potential credits” and “debits”. Potential credits represent the potential environmental benefits resulting from the overall recovery of food products destined for waste, while debits indicate the environmental impacts associated with the different stages of the process, including storage, transport, and disposal of the products.

In terms of potential credits, the factors as ‘intercepted product’, ‘transport for intercepted product’ and ‘packaging for intercepted product’ have significantly negative values, indicating a strong potential positive impact in terms of greenhouse gas emission savings associated with the potential recovery of the product. The importance of the Foody Hub lies in the prevention of food waste and the reduction of the environmental impact; in fact, the greater the number of potential credits protected by avoiding food waste, the greater the environmental benefit (resulting in EIB <0).

On the contrary, some phases contribute to environmental debts, indicated by positive values. The main contributors to these debts are related to Intercepted product wasted, Transport related to intercepted product wasted and Intercepted product packaging wasted which show respectively 11%, 4% and 2% of weight among the impact categories. On the other hand, the minimum values for “Internal logistics for intercepted products”, “Internal waste logistics” and “Waste treatment” suggest relatively low environmental impacts associated with internal logistics and waste treatment processes.

Considering the entire scenario, an overall negative balance is observed, indicating a net production of environmental credits. It is essential to note that the analysis is related to an interception process of vegetable commodities destined for waste, leading to associated debts in different process phases. However, the benefits derived from the recovery process, along with the subsequent avoidance of new product production and food distribution, outweigh the negative impacts.

Within the environmental impacts, the analysis shows that fresh produce production is the leading cause of impact in almost all categories, accounting on average for 63% of the total impact. Food transport is the second most important factor, contributing 26.9% on average. When analyzing the individual impact categories, cucumbers, peaches, peppers, artichokes, and tomatoes were identified as the products with the highest environmental impact among the stored products. The storage phase at the Foody Hub has a negligible environmental impact. In the context of the Climate Change impact category, the complete interception of fresh produce has prevented the emission of more than 169 tons of CO_2 equivalent, leading to a notable decrease in the overall impact of Climate Change. The rescued products have generated substantial environmental credits, reflecting negative values in various categories, and highlighting a significant reduction in impact compared to the typical life cycle of these products.

However, the process generates environmental liabilities due to the production, transport and disposal of waste during the product sorting phase. These environmental impacts can be identified in Table 5 in the red-coloured sections (waste processes, distribution processes). Despite this challenge, a well-coordinated group of volunteers and a designated

Table 6
Environmental impact per FU related to the different phases of the product life cycle identified as credits and debits. CC: Climate Change; OD: Ozone Depletion; IR: Ionizing Radiation; POF: Photochemical Ozone Formation; PM: Particulate Matter; HT-NC: Human Toxicity, Non-Cancer; HT-C: Human Toxicity, Cancer; ACID: Acidification; EU-F: Eutrophication, Freshwater; EU-M: Eutrophication, Marine; EU-T: Eutrophication, Terrestrial; ECOTOX: Ecotoxicity, Freshwater; LU: Land Use; WU: Water Use; RU-F: Resource Use, Fossils; RU-M: Resource Use, Minerals and Metals.

		Upstream processes				Potential credits (total)	Waste processes							Distribution processes		Debits (total)	EIB (total)
		Intercepted product	Packaging for intercepted product	Transport for intercepted product	Internal logistic for intercepted product		Intercepted product wasted	Intercepted product packaging wasted	Transport related to intercepted products wasted	Waste internal logistic	Waste transport	Waste treatment	Packaging waste treatment	Storage at the Foody Hub	Transport from the Foody Hub to the needy people		
CC	kg CO2 eq	$-1.1x10^{+05}$	$-2.7x10^{+04}$	$-5.9x10^{+04}$	$-1.8x10^{+01}$	$-2,0x10^{+05}$	$1.13x10^{+04}$	$3.77x10^{+03}$	$7.62x10^{+03}$	2.64	$1.38x10^{+03}$	$2.99x10^{+03}$	$1.10x10^{+03}$	$8.22x10^{+01}$	$7.03x10^{+03}$	$3,53x10^{+04}$	$-1,6x10^{+05}$
OD	kg CFC11 eq	$-1.0x10^{-02}$	$-1.2x10^{-03}$	$-1.3x10^{-02}$	$-2.5x10^{-06}$	$-2.5x10^{-02}$	$2.27x10^{-03}$	$1.70x10^{-04}$	$1.72x10^{-03}$	$3.59x10^{-07}$	$2.99x10^{-04}$	$5.90x10^{-05}$	$2.34x10^{-05}$	$1.76x10^{-06}$	$1.44x10^{-04}$	$4.69x10^{-03}$	$-2.0x10^{-02}$
IR	kBq U-235 eq	$-3.0x10^{+03}$	$-2.0x10^{+03}$	$-3.7x10^{+03}$	-2.5	$-8.7x10^{+03}$	$3.78x10^{+02}$	$2.78x10^{+02}$	$4.73x10^{+02}$	$3.62x10^{-01}$	$8.39x10^{+01}$	$2.48x10^{+01}$	6.60	$1.02x10^{+01}$	$2.80x10^{+02}$	$1.53x10^{+03}$	$-7.2x10^{+03}$
POF	kg NMVOC eq	$-5.2x10^{+02}$	$-8.6x10^{+01}$	$-5.0x10^{+02}$	$-4.0x10^{-02}$	$-1.1x10^{+03}$	$5.36x10^{+01}$	$1.18x10^{+01}$	$6.30x10^{+01}$	$5.71x10^{-03}$	$1.35x10^{+01}$	4.77	1.22	$2.37x10^{-01}$	$4.55x10^{+01}$	$1.94x10^{+02}$	$-9.2x10^{+02}$
PM	disease inc.	$-1.0x10^{-02}$	$-1.1x10^{-03}$	$-3.9x10^{-03}$	$-3.2x10^{-07}$	$-1.5x10^{-02}$	$1.25x10^{-03}$	$1.51x10^{-04}$	$5.07x10^{-04}$	$4.58x10^{-08}$	$1.94x10^{-04}$	$7.88x10^{-05}$	$1.48x10^{-05}$	$1.35x10^{-06}$	$6.85x10^{-04}$	$2.88x10^{-03}$	$-1.2x10^{-02}$
HT-NC	CTUh	$-1.0x10^{-02}$	$-2.1x10^{-04}$	$-7.2x10^{-04}$	$-1.0x10^{-07}$	$-1.1x10^{-02}$	$1.48x10^{-03}$	$2.95x10^{-05}$	$9.33x10^{-05}$	$1.50x10^{-08}$	$7.12x10^{-06}$	$6.27x10^{-05}$	$3.87x10^{-06}$	$5.00x10^{-07}$	$1.32x10^{-04}$	$1.81x10^{-03}$	$-1.0x10^{-02}$
HT-C	CTUh	$-1.4x10^{-04}$	$-9.1x10^{-06}$	$-3.1x10^{-05}$	$-4.1x10^{-09}$	$-1.8x10^{-04}$	$2.44x10^{-05}$	$1.24x10^{-06}$	$4.07x10^{-06}$	$5.90x10^{-10}$	$1.88x10^{-07}$	$7.53x10^{-07}$	$1.02x10^{-07}$	$2.10x10^{-08}$	$1.04x10^{-05}$	$4.11x10^{-05}$	$-1.4x10^{-04}$
ACID	mol H+ eq	$-9.5x10^{+02}$	$-1.1x10^{+02}$	$-5.2x10^{+02}$	$-8.4x10^{-02}$	$-1.6x10^{+03}$	$1.26x10^{+02}$	$1.61x10^{+01}$	$6.49x10^{+01}$	$1.20x10^{-02}$	8.70	4.77	$8.44x10^{-01}$	$2.85x10^{-01}$	$3.20x10^{+01}$	$2.54x10^{+02}$	$-1.3x10^{+03}$
EU-F	kg P eq	$-3.4x10^{+01}$	-7.2	-4.5	$-4.2x10^{-03}$	$-4.6x10^{+01}$	3.42	$9.88x10^{-01}$	$5.82x10^{-01}$	$6.01x10^{-04}$	$2.47x10^{-02}$	$2.69x10^{-01}$	$5.02x10^{-03}$	$1.25x10^{-02}$	$9.16x10^{-01}$	6.22	$-4.0x10^{+01}$
EU-M	kg N eq	$-4.0x10^{+02}$	$-2.3x10^{+01}$	$-1.7x10^{+02}$	$-1.2x10^{-02}$	$-5.9x10^{+02}$	$5.87x10^{+01}$	3.27	$2.13x10^{+01}$	$1.83x10^{-03}$	3.50	$7.17x10^{-01}$	$8.38x10^{-01}$	$4.86x10^{-02}$	$1.08x10^{+01}$	$9.91x10^{+01}$	$-5.0x10^{+02}$
EU-T	mol N eq	$-2.6x10^{+03}$	$-2.3x10^{+02}$	$-1.8x10^{+03}$	$-1.4x10^{-01}$	$-4.8x10^{+03}$	$4.45x10^{+02}$	$3.26x10^{+01}$	$2.32x10^{+02}$	$2.04x10^{-02}$	$3.84x10^{+01}$	6.27	3.79	$5.52x10^{-01}$	$1.16x10^{+02}$	$8.75x10^{+02}$	$-3.9x10^{+03}$
ECOTOX	CTUe	$-7.9x10^{+06}$	$-3.5x10^{+05}$	$-7.2x10^{+05}$	$-1.7x10^{+02}$	$-9.0x10^{+06}$	$1.17x10^{+06}$	$4.77x10^{+04}$	$9.25x10^{+04}$	$2.52x10^{+01}$	$1.05x10^{+04}$	$6.16x10^{+04}$	$2.91x10^{+03}$	$1.51x10^{+02}$	$4.70x10^{+04}$	$1.44x10^{+06}$	$-7.5x10^{+06}$
LU	Pt	$-3.1x10^{+06}$	$-3.8x10^{+05}$	$-3.8x10^{+05}$	$-5.1x10^{+01}$	$-3.8x10^{+06}$	$5.07x10^{+05}$	$5.20x10^{+04}$	$4.97x10^{+04}$	7.37	$3.30x10^{+03}$	$3.96x10^{+03}$	$4.23x10^{+02}$	$2.03x10^{+02}$	$3.96x10^{+04}$	$6.56x10^{+05}$	$-3.2x10^{+06}$
WU	m3 depriv.	$-4.4x10^{+05}$	$-1.0x10^{+04}$	$-2.9x10^{+03}$	$-1.2x10^{+01}$	$-4.6x10^{+05}$	$8.04x10^{+04}$	$1.40x10^{+03}$	$3.73x10^{+02}$	1.75	$1.69x10^{+01}$	$6.02x10^{+01}$	$4.93x10^{+01}$	$4.97x10^{+01}$	$4.70x10^{+02}$	$8.28x10^{+04}$	$-3.7x10^{+05}$
RU-F	MJ	$-9.6x10^{+05}$	$-7.1x10^{+05}$	$-7.9x10^{+05}$	$-2.8x10^{+02}$	$-2.4x10^{+06}$	$9.74x10^{+04}$	$9.70x10^{+04}$	$1.02x10^{+05}$	$3.99x10^{+01}$	$1.88x10^{+04}$	$8.85x10^{+03}$	$1.53x10^{+03}$	$1.24x10^{+03}$	$9.63x10^{+04}$	$4.23x10^{+05}$	$-2.0x10^{+06}$
RU-M	kg Sb eq	$-4,4x10^{-01}$	$-1,2x10^{-01}$	$-3,0x10^{-01}$	$-4,0x10^{-05}$	$-8.7x10^{-01}$	$6,66x10^{-02}$	$1,75x10^{-02}$	$3,86x10^{-02}$	$5,70x10^{-06}$	$1,20x10^{-03}$	$2,15x10^{-03}$	$1,60x10^{-04}$	$1,40x10^{-04}$	$5,58x10^{-02}$	$1.82x10^{-01}$	$-6.9x10^{-01}$

facility at the Ortomercato for the collection, sorting and storage of fruit and vegetables are demonstrating an effective approach to reducing food waste, significantly reducing the environmental consequences of the food sector.

At the Foody Hub, RECUP APS implements food donation activities, configuring an environmentally sustainable practice that generates tangible benefits by reducing greenhouse gas emissions and minimizing the overall environmental footprint through the ‘carbon avoidance’ approach. The overall analysis suggests that, despite some challenges, the intercepting of fruit and vegetable surpluses from the waste stream significantly contributes to environmental sustainability, confirming the importance of initiatives to reduce food waste and manage resources wisely.

Moreover, intercepting fruit and vegetable surpluses offers significant economic advantages even if not considered directly in this study. While in the system analysed there are operational costs like transportation, sorting, and manpower, the initiative prevents the economic loss of wasted food. Additionally, by reducing the need for new production, a lot of resources like water and fertilizers may be saved, reducing also transportation and storage costs. By preventing new production cycles, the initiative reduces the demand for resources, lowering the economic burden of acquiring them. Additionally, it mitigates the economic costs associated with environmental damage caused by conventional food production. Therefore, despite incurring operational expenses, the economic significance lies in resource conservation, market creation, and reduction of the economic burden of environmental externalities from food production.

6. Conclusion

The Life Cycle Assessment (LCA) analysis, conducted concerning the operations of a non-profit association operating at the Ortomercato, has revealed that organizing activities can significantly ensure ongoing distribution to those in need and enhance the endeavors of other stakeholders engaged in redistribution.

The possibility of having a dedicated space within the Ortomercato, thanks to food policies, allows the development and adoption of operational practices aimed at ensuring control over the quality of surpluses and a better logistical management, allowing for the attainment of environmental credits.

The results of the quantitative and environmental impact analysis suggest that an organisation operating within the market is highly successful in food recovery, saving over 136 tonnes of food during the 49-day period of operation at the market alone and generating environmental carbon credits equivalent to 169 tonnes of CO_2 eq. in a year. The detailed analysis highlighted how some products are more likely to be donated, while others, such as peaches, despite being one of the most donated products, represent the most discarded product at the screening stage, accounting for approximately 21% of the total crop (most likely due to the perishable nature of the product).

This study establishes a strong foundation for advocating the efficiency of the Foody Hub model in minimizing food waste through the efforts of non-profit organizations. It also makes a positive contribution to the environment in situations where safeguarding the value of food products is a primary concern. The undertaken analysis has revealed that systems incorporating recovery methods not only ensure the fulfilment basic needs of individuals in challenging situations but also offer the potential to significantly decrease food waste. Public food policy can greatly benefit from adopting the Foody Hub model, as demonstrated by this study. By leveraging non-profit organizations, this model efficiently minimizes food waste while simultaneously addressing the pressing issue of food insecurity. This approach not only contributes positively to environmental sustainability but also ensures the preservation of the value of food products. Looking forward, future research could further investigate the optimization of recovery methods, explore innovative technologies, and enhance cross-sector collaboration to maximize the sustainability and effectiveness of food recovery and redistribution initiatives. To comprehensively quantify the economic significance of the analysed system with objective results, a more comprehensive cost-benefit analysis might be necessary for a complete picture. Additionally, introducing a user-friendly practical tool to enhance the sustainability of the agri-food system at Foody HUB could be beneficial. Moreover, investigating consumer behavior and perception towards recovered food products could provide valuable insights into fostering acceptance and adoption of such practices, thereby further advancing efforts towards a more environmentally sustainable and resilient food system.

CRediT authorship contribution statement

Andrea Casson: Writing – original draft, Visualization, Software, Methodology, Investigation, Data curation, Conceptualization. **Giovanni Ferrazzi:** Writing – review & editing, Resources, Methodology, Investigation, Conceptualization. **Riccardo Guidetti:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Carlo Bellettini:** Writing – original draft, Resources, Methodology, Data curation, Conceptualization. **Abhishek Dattu Narote:** Writing – original draft, Visualization, Software, Methodology. **Manuela Rollini:** Writing – review & editing, Visualization, Resources, Conceptualization. **Alberto Piccardo:** Writing – review & editing, Resources, Data curation. **Elena Volturo:** Writing – review & editing, Resources, Data curation. **Marcello Cosentino:** Writing – review & editing, Resources, Data curation. **Sara Limbo:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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