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Redistribution through urban food hubs: A comprehensive sustainability assessment

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A R T I C L E I N F O

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A B S T R A C T

Urban food hubs are a novel operational model for surplus food redistribution, and an increasingly implemented policy instrument to mitigate synergically food waste and food insecurity. However, there is still need to assess comprehensively their sustainability impacts across the environmental, social and economic dimensions. This study focuses on Milan, a frontrunner city in the implementation of innovative food policies, where urban food hubs aim to generate positive impacts in food waste reduction and food insecurity mitigation through a neighborhood-based and quick redistribution model. Methodologically, the study performs a comprehensive, multi-dimensional (environmental, social and economic) sustainability evaluation using life cycle assessment, net economic benefit calculation and social sustainability indicators evaluation. Results show that one food hub offers annual net savings of 107 t of CO_2 equivalent and generates substantial environmental benefits across different environmental dimensions. Robustness checks and sensitivity analyses are carried out considering different degrees of displacement impacting the level of substitution of redistributed products. Regarding the social dimension, one food hub recovers every year approximately 140,000 meals for 3000 beneficiaries, and successfully integrates fresh food (fruit, vegetables, fresh proteins) as key nutritional components. At the same time, the economic value of recovered food is 12.21 times the costs sustained to recover and redistribute it. The results also unpack the environmental impact of each phase of the process, from avoided production until redistribution. These results quantify and provide a framework to assess the environmental, economic and social sustainability of food hubs as an urban food policy instrument.

1. Introduction

Improving the sustainability of food systems is a critical challenge for sustainable development (Casson et al., 2023; Domingo-Morcillo et al., 2024). The coexistence of food waste and food insecurity is one of the most urgent global challenges for food systems (Treutwein and Langen, 2021). While 113 million people suffer from severe hunger (United Nations Environment Programme, 2024) and 733 million are food insecure (FAO; IFAD; UNICEF; WFP; WHO, 2024), almost one-third of the food produced worldwide is wasted (FAO, 2011). Beyond the social and economic unsustainability of wasting food among widespread food insecurity, the unnecessary production and distribution of wasted food leads to sizeable environmental impacts – in terms of contribution to GHG emissions and climate change (Amicarelli et al., 2021; Zhu et al., 2023), resource depletion (Domingo-Morcillo et al., 2024), water and air pollution (Gatto and Chepeliev, 2024; Guo et al., 2023), and biodiversity loss (Guo et al., 2023). It is therefore fundamental to gain a better understanding of the impacts of different strategies for food redistribution and food waste reduction (Wang et al., 2024; Valentini et al., 2025).

Reducing food waste and insecurity in cities is a policy priority (Filippini et al., 2019), and it is vital to achieving Sustainable Development Goal (SDG) 2 (Zero Hunger), particularly Target 2.1 on ensuring access to safe, nutritious food, SDG 12 (Responsible Consumption and Production), especially Target 12.3, which aims to halve global food waste by 2030, and SDG 11 (Sustainable Cities and Communities) (United Nations, 2015). In fact, over the past two decades, food access has gained increasing importance within urban planning systems and public policy (Cohen, 2022), given the concentration of food poverty

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and inequalities and the generation of food waste in cities (Bartezzaghi et al., 2025). Recovering and redistributing surplus food to the needy seems to be key to simultaneously tackling both issues (Garrone et al., 2014; Papargyropoulou et al., 2014; Thapa Karki et al., 2021) and to achieve the best environmental impacts (Muñoz-Torres et al., 2025). This paper contributes to this important debate by providing a complete sustainability (environmental, social and economic sustainability) evaluation of the impacts of the two main food hubs in the city of Milan. Milan is at the forefront of the implementation of innovative food policies, leading an international network of cities under the Milan Urban Food Policy Pact (Filippini et al., 2019). Its collaborative food hubs (Bartezzaghi et al., 2025) are a prominent case study for their novel operational model, and they have been recognized extensively at the international level, winning the Earthshot Prize in 2021.

Our article is innovative compared to existing literature because it expands current knowledge in terms of methods and results on the impacts of urban food redistribution. Numerous studies have examined managerial and policy solutions to mitigate urban food waste and food insecurity (Ghinoi et al., 2020; Papargyropoulou et al., 2014), yet food redistribution has been studied mainly through more conventional models of food banking (Sundin et al., 2023) or social supermarkets (Damiani et al., 2021), and mostly looking at their environmental impact (Casson et al., 2024; Damiani et al., 2021; Sundin et al., 2022) with limited attention to the social dimension (Sundin et al., 2023). Our research focuses on urban food hubs as a novel arrangement, defined as "systems aimed at providing access to sufficient and nutritious food to vulnerable people through a surplus food redistribution network of small warehouses located in different neighborhoods of a city" (Bartezzaghi et al., 2025), and it is the first to provide a comprehensive impact assessment including the environmental, social, and economic sustainability of this model. As an innovative model for food recovery and redistribution, urban food hubs have received considerable policy attention (Earthshot Prize, 2021) and, while literature preliminarily suggests their higher effectiveness compared to traditional models of food banking (Bartezzaghi et al., 2025; Bartezzaghi et al., 2022; Casson et al., 2024; Papargyropoulou et al., 2024), a more systematic understanding of their impacts is needed (Casson et al., 2024; Papargyropoulou et al., 2024). Such understanding is crucial to quantify food hubs' value for communities and the environment (Casson et al., 2024; Papargyropoulou et al., 2024; Sundin et al., 2023; Vittuari et al., 2017) and allow them to reach long-term operational stability (Casson et al., 2024; Trejo-Pech et al., 2023). Indeed, financial stability is a key requirement for food hubs' medium and long-term viability, which is a consequence of the recognition of their benefits to local communities and the wider food system in terms of food security, environmental sustainability and resilience (Bartezzaghi et al., 2025; Moggi and Dameri, 2021; Papargyropoulou et al., 2024). Finally, in contrast to prior studies focusing primarily on surplus fruits and vegetables (Casson et al., 2024), our study expands the scope significantly by studying urban food hubs that redistribute a wide range of food categories. This broader approach provides a more holistic understanding of how redistribution through urban food hubs of different food types contributes across environmental, social, and economic dimensions.

2. Methods

2.1. Description of the system and objective

The objective of the food hubs in Milan is to collect unsold surplus food from retailers, which would otherwise be destined for disposal, and to redistribute it to beneficiaries. Food hubs operate at the neighborhood scale, collecting surplus food from local retailers and redistributing it to local food aid nonprofit organizations (Bartezzaghi et al., 2025). For the sake of clarity, surplus food is defined as safe and edible food that is produced, manufactured, distributed, or served but for various reasons is unsold or unconsumed for its intended purpose, while food waste denotes previously edible food that is no longer safe for human consumption (Garrone et al., 2014). Due to various factors, mainly related to approaching the expiration date, or issues with packaging or aesthetic standards, products are removed from the shelves even though they still fit for human consumption (Bartezzaghi et al., 2022; Teller et al., 2018). Nonprofit organizations that manage the hubs recover surplus from the points of sale and transport it to the food hubs, where smaller front-line nonprofit organizations assisting underprivileged citizens pick balanced food mixes to redistribute to the needy. The objective of this analysis is to assess the environmental, economic and social impacts associated with the recovery of surplus food and its redistribution for human consumption through the model of urban food hubs.

2.2. Functional unit, reference flow and system boundaries

The functional unit is the service provided by one hub in an average year. The reference flow corresponds to the amount of surplus food recovered from the waste stream and redistributed in one year. The chosen functional unit is coherent with existing literature (Casson et al., 2024), and it represents a manageable and concrete operational scale that reflects the typical lifecycle and activities of a municipal food hub. It enables the aggregation of environmental impacts over a defined temporal horizon and supports consistent comparisons across different operational models, design scenarios, or geographical implementations (Jablonski et al., 2016). Furthermore, this unit aligns with policy-relevant planning cycles (e.g., annual budgets), making it a practical reference for scenario-based assessments and institutional decision-making. The chosen functional unit (annual operations of one food hub) allows indeed for comparisons across hubs of different scales, since the results can be normalized per meal recovered or per kilogram of food redistributed, ensuring scalability and cross-hub comparability. The study is conducted with a "cradle-to-gate" approach, where the "cradle" represents the production of food, and the "gate" corresponds to the moment when the recovered products are donated to the final beneficiary. As represented in Fig. 1, the following processes are included:

1. Product at retail: Surplus food production, packaging, distribution
2. Avoided waste: Avoided food waste for the municipal solid waste (MSW) management system
3. Collection: Recovery of unsold food through donation
4. Storage (Energy): Energy consumption at the hubs, primarily for positive cold storage
5. Storage (Waste): Food waste generated at the hubs
6. Redistribution: Surplus food redistribution to nonprofit organizations.

2.3. Data collection

Primary data have been directly collected from the food hub managers. These are surplus food flows, recovery routes including collection (from donor retailers), delivery points (front-line food aid nonprofit organizations) and beneficiaries reached related to the two main food hubs in Milan (Isola and Lambrate). Data on food recovered is expressed in weight and disaggregated into product classes (Table 1). Further data, i.e. operational costs for recovery and redistribution, the disaggregated composition of product classes, have been collected through interviews with donor retailers and organizations managing the hubs. The economic value of recovered products for each product class (€/kg) is based on the average price reported by retailers for donated items.

2.4. Inventory modelling framework

2.4.1. Allocation method

Mass-based allocation was employed to ensure that the environmental and economic impacts of the system were distributed proportionally among its outputs based on their physical weight.

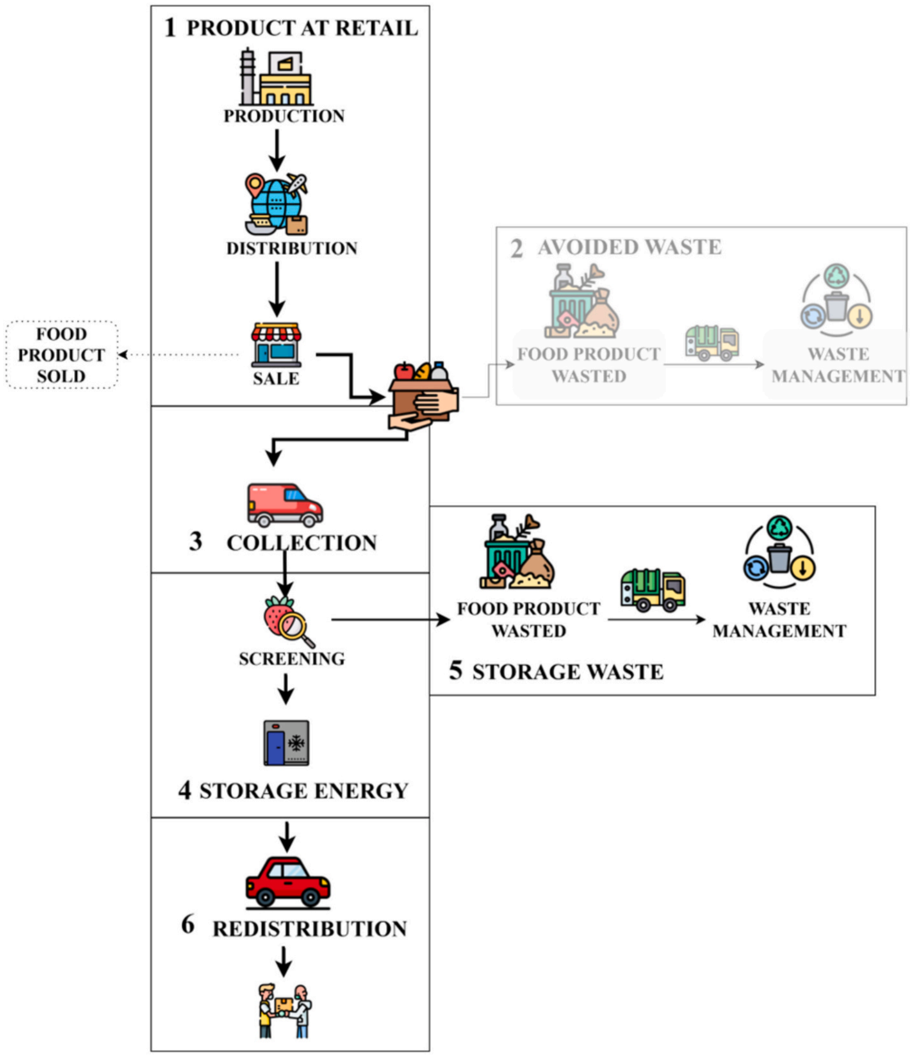

Fig. 1. Representation of phases in the "cradle-to-gate" approach. Six phases of surplus food go through from the initial stages of production until it is recovered and redistributed through food hubs, expressed by the reference flow.

Table 1
Product classes and categories as per the functional unit.

Product class	Product category
Dry/various	Drinks Other dry products Childhood products Oil and sauces Pasta Rice
Bread	Fresh bread Dry bread
Bakery	Pastry Cookies
Fruit and vegetables	Fresh fruit Preserved fruit Preserved vegetables/legumes Fresh vegetables
Meat	Meat
Fish	Fish
Cooked food	Cooked food and cured meat
Dairy	Milk Yogurt Cheese

2.4.2. Temporal and geographical representativeness

The study focused on the activities of the two main food hubs in Milan (Isola and Lambrate) between January 2022 and July 2024 (31 months). The evaluation involved the analysis of several aspects. A detailed description of all these factors is given in the following sections.

2.5. Inventory analysis

Table 2 summarizes the data sources. The main reference source is the data collection and monitoring database created within the Milan's Neighborhood Hubs Against Food Waste project (Bartezzaghi et al., 2025). It is a database where data is collected monthly, both at the individual retailer level for each store that donates surplus food, and for each Hub through the documentation provided by the nonprofit organizations in charge of activities. In addition to the volumes of surplus food recovered, information is also collected on the network structure, which includes for each hub the name and location of the points-of-sale that donate food products and the data on the final beneficiaries (location of front-aid nonprofits receiving the surplus food, number of households and total beneficiaries served). Data on surplus food covers the quantity and economic value of donated and disposed food products. The information is disaggregated according to the product categories

Table 2
Summary of data sources across life cycle stages as per the reference flow.

Hub process		Value	Remarks	Source
Product at retail	Kg	70,401.68	Surplus food recovered at the supermarket	Primary data from food hubs monitoring system
Avoided waste	Kg	70,401.68	MSW collection truck travels an average of 30 km within the city	Primary data from food hubs monitoring system, Interview with food hub managers
Collection	Kg	70,401.68	Collection trucks travel an average of 14,760 km/year	Interview with food hub managers
Storage: Energy	kWh	7008.62	Products are stored in refrigerated areas	Data from food hub energy bills
Storage: Waste	Kg	704.02	1 % of collected food subject to waste	Interview with food hub managers
Redistribution	Kg	69,697.66	Redistributed through nonprofits, average 7549.46 km/year	Primary data from food hubs monitoring system, Interview with food hub managers

shown in Table 1. For the analysis, the data in this database were then supplemented through detailed interviews with different managers involved at both coordination and operational levels in the donation and management of surplus food in the Hubs. These interviews were accompanied by field visits and direct observations integrated through email exchanges, written notes, scans of energy bills and phone calls to retrieve the necessary data on the process variables. To ensure the accuracy of the data, once collected, they were compared with the ones published in policy briefs and reports, and other publicly available material by the Milan municipality. For the stages of the process on which primary data could not be collected, reference was made to reliable LCA databases and approaches available in literature and used in similar studies (Casson et al., 2024).

2.5.1. *Product at retail*

To assess the environmental impact of the production, packaging and distribution activities associated with the product that can be recovered through diverting it from waste, the databases Ecoinvent v.3.10 and Agribalyse v.3.1 were used. They include information on food products at retail level, considering the average European transportation and the related packaging. From the two databases, a total of 657 datasets were selected as representative of food products handled by the hubs. Each dataset provided an average value for each food product category. Finally, the exclusion of certain products was based on feedback received during interviews with the hub managers. The product at retail is included in the study as a positive environmental impact. The assumption is that in the absence of recovery and redistribution activities, a product with an equivalent environmental impact would have to be produced and distributed to provide the final beneficiary with the same product and nutritional value. To reflect realistic production and consumption behaviour, five displacement scenarios (100 %, 75 %, 50 %, 25 %, and 0 %) were also modelled.

In economic terms, the surplus donated by retailers represented a positive economic impact generated, as it represents a recovery of economic value without it being wasted. This is represented by the average sale price reported by retailers for the donated food items. This value also corresponds to the avoided monetary costs for the food aid organizations (or directly for the beneficiaries) since these products are donated and do not have to be purchased. Additional items considered are the savings related to the avoided food waste management for the retailer (quantified in 120 €/t in the Municipality of Milan (Comune di Milano, 2020).

2.5.2. *Avoided waste*

Since food is donated, it is not conferred to the waste management system. Through the MSW management system, waste collection trucks travel an average of 30 km (km) and deliver the food product for treatment (as reported by the municipality of Milan (Lucas et al., 2023), 50 % is composted and the remaining 50 % turned into biogas). This avoided waste represents an environmental credit.

2.5.3. *Collection*

Logistic data were obtained from the collection routes of the Isola and Lambrate hubs. The van in Isola travels an average of 61 km per day, while the Lambrate one travels an average of 62 km per day. Collection of food products is performed once a week. For each collection round, the corresponding emissions were calculated, considering the use of refrigerated transport. As part of the economic evaluation of transport, the Automobile Club d'Italia (ACI) platform was used to estimate the average cost per km for the vehicle used, yielding a value of 0.36 €/km. This cost includes proportional costs (such as capital share, fuel, tires and maintenance and repairs expressed in €/km).

2.5.4. *Storage: energy*

Energy consumption obtained from energy bills of the hubs, primarily for positive cold storage, was quantified in 7008.62 kW-hour (kWh)/year. In the environmental analysis, the Italian residual energy mix was considered, while the national average cost per kWh was used for the economic evaluation. In the case of 2022, a cost of 0.70 €/kWh was quantified, in 2023 equal to 0.38 €/kWh and in 2024 equal to 0.37 €/kWh.

2.5.5. *Storage: waste*

Approximately 1 % of donated products become waste after quality checks at the hubs. Through the municipal waste management system, waste collection trucks travel an average of 30 km and deliver food products for treatment (50 % composted and 50 % biogas). The percentage of waste equivalent to 1 % and 5 % was modelled respectively as paper waste and plastic waste for food packaging. The Italian waste management scenario was selected as representative of these waste streams.

2.5.6. *Redistribution*

Redistribution involves front-line food aid nonprofit organizations collecting products from the hubs and delivering them to beneficiaries. The average distance covered by front-line organizations was calculated through Google Maps, and transport was modelled using representative data of petrol-powered and diesel-powered cars (Euro 5), based on data from the Ecoinvent 3.10 database. In the case of the economic analysis, this phase was once again modelled using ACI tables and an average of 0.45 €/km was identified as cost. According to the Italian Reference Nutrient Intake Levels (LARN), 500 g of food is identified as an equivalent dish. This value was used as a reference for the calculation of the social impact.

2.6. *Multi-dimensional sustainability assessment*

Following the objective of the study, the results of the analysis are proposed following the three sustainability dimensions. In line with literature, the methodology used to assess the sustainability of the project is based on Life Cycle Assessment (LCA) for the environmental assessment (Casson et al., 2024), and on the net economic benefit calculation based on the difference in economic benefits created for the system through the redistribution activities and the overall cost of these activities for the economic assessment (Sundin et al., 2023). The social sustainability impact assessment, instead, since it has received the least attention in literature and is less measurable, relies on indicators referring to the number of meals donated, food-insecure people supported, households reached and food banks supplied (Sundin et al., 2022).

2.6.1. *Environmental assessment*

To assess the environmental impact, the software SimaPro version 9.6.0.1 (PRé Sustainability) was used, together with the databases Ecoinvent v 3.10 and Agribalyse v 3.1. The analysis was conducted following cut-off allocation criteria, which exclude upstream processes related to discarded products from the system. This approach ensures a clear distinction between waste streams that are avoided and those that remain in the system. The life cycle assessment phase requires assessing potential environmental impacts by analyzing life cycle inventory data. This step involves linking pollutant flow data with specific environmental impact categories. Environmental impacts are then calculated for each life cycle stage, including the collection, storage and redistribution of recovered food.

2.6.2. *Economic assessment*

In economic terms, the analysis was conducted using an annual net economic benefit analysis. This indicator considers the value of the recovered food products (including the avoided costs of food waste

Fig. 2. Analysis of mass flows. a. Box plot representation of the monthly recovered food volumes in the two hubs. **b.** Box plot representation of the different food categories recovered in the two hubs. **c.** Average annual recovered volumes for the two food hubs expressed per reference flow.

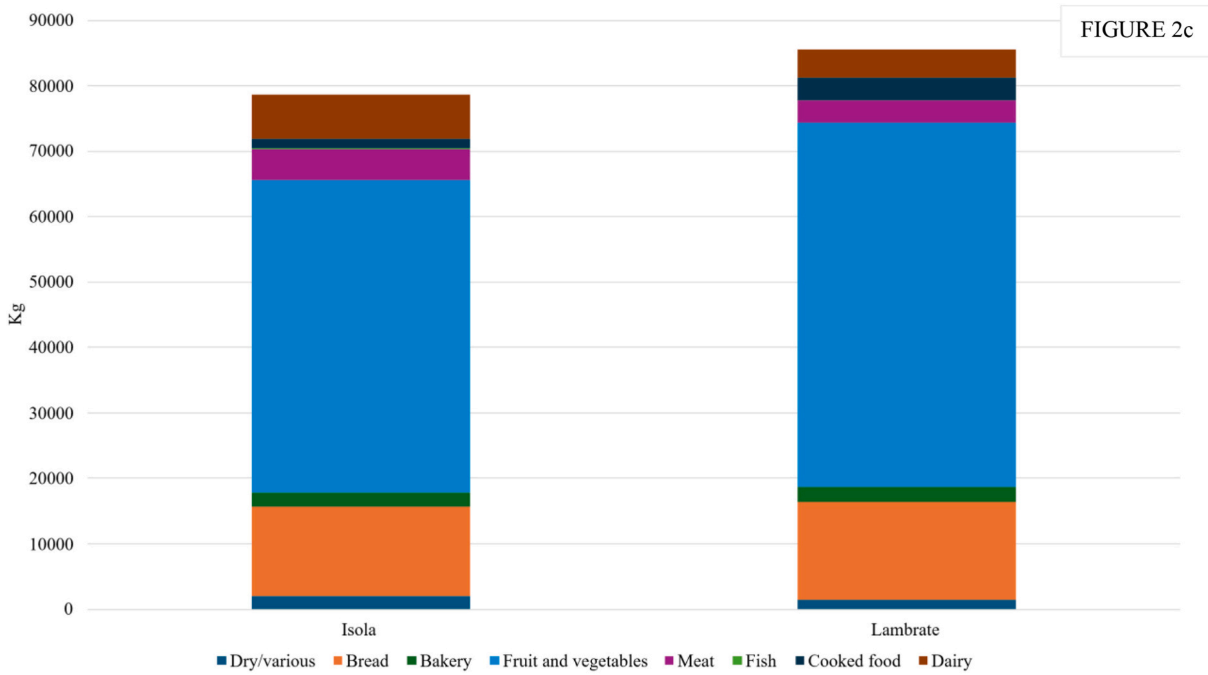

Fig. 2. (*continued*).

disposal) and the operational costs necessary for their recovery and redistribution. This indicator allows an assessment of the economic sustainability of food hubs, providing useful information to determine the operational efficiency and overall economic value generated by the recovery of food that would otherwise have been wasted.

2.6.3. *Social assessment*

For the evaluation of the social impact, we performed a social sustainability indicators evaluation. The number of equivalent meals distributed, the number of people assisted, and the number of equivalent meals provided per beneficiary by the food hubs were considered as indicators, providing a quantitative measure of the contribution to reducing food insecurity and supporting vulnerable people.

3. Results

Results are presented in two sections: (i) an analysis of the mass flows referring to the different categories of recovered and redistributed products, (ii) a comprehensive assessment of environmental, social and economic sustainability dimensions.

3.1. *Analysis of mass flows*

The mass flow analysis of the two food hubs for 31 months (from January 2022 to July 2024) reveals notable trends in the recovered food volumes and their composition. Fig. 2a shows the box plot illustrating the quantities donated to the hubs and the seasonal variations in monthly volumes across the years analysed. Excluding August (where food hubs are mostly not operational), average recovered volumes range between slightly more than 4 t (December) and 8.2 t (March). Analyzing the averages ± standard deviation (SD) in recovered volumes, the months of February (7.0 ± 2.0 t), September (5.3 ± 1.9 t), October (6.1 ± 1.9 t) and November (6.8 ± 2.5 t) showed high fluctuations, while April (6.3 ± 0.9 t) and May (6.8 ± 1.0 t) showed a lower variance. These differences suggest the higher management complexity of some periods which are characterized by more uncertain flows.

Fig. 2b reveals that fresh fruit and vegetables make up the largest share of recovered products at both hubs. In particular, fresh vegetables showed the highest volumes, with an annual average of 28.55 t (39 %), with a peak of 35.45 t at Lambrate in 2023. Fresh fruit had a yearly average of 17.33 t (24 %). Fresh bread, the third largest category, averaged 11.88 t (16 %), while dairy and meat followed with 4.9 t (7 %) and 3.59 t (5 %). This suggests the necessity to focus on those categories with higher donation rates to optimize their storage and redistribution.

Differences in recovery patterns between the two hubs were considerable, as illustrated in Fig. 2c. Lambrate collects 8.7 % more bread (14.9 t vs. 13.7 t) and 16.7 % more fruit and vegetables (55.7 vs. 47.7 t), while Isola showed higher recovery rates for meat (+42.4 %, 4.7 vs. 3.3 t) and dairy (+59.5 %, 6.7 vs. 4.2 t). Isola recovered more dry goods (+35.7 %, 1.9 vs. 1.4 t), whereas Lambrate recovered more cooked food (+126.6 %, 3.4 vs. 1.5 t). These differences suggest the possibility of improving the product mix through exchanges between the two locations and improving the nutritional balance for beneficiaries.

The total recovered volumes displayed a slight downward trend. In 2022, the hubs recovered 145.92 t (74.99 t from Isola and 70.93 t from Lambrate). This total decreased slightly to 133.21 t in 2023 (53.12 t from Isola and 80.10 t from Lambrate). In the first seven months of 2024, the hubs recovered 84.62 t (43.85 t from Isola and 40.77 t from Lambrate). These findings suggest stable recovery volumes, underscoring the resilience of the hubs' operations.

3.2. *Results of the sustainability assessment*

3.2.1. *Environmental assessment*

The environmental sustainability of the food hubs was assessed through a comprehensive life cycle assessment, considering both environmental credits and debts. Fig. 3 presents the hotspot analysis by Functional Unit (per hub), with Fig. 3a showing the environmental credits, Fig. 3b showing the environmental debts, and Fig. 3c showing the overall balance. The environmental impact balance of this service assesses both the environmental credits (derived from avoided impacts) and the environmental debts (generated by the recovery and

Fig. 3. Environmental assessment results. Representation of the credits **(a.)**, the debts **(b.)** and the net environmental balance **(c.)** for the different environmental impact categories as per the functional unit.

Note: Acidification Potential (ACID, mol H^+ eq), Climate Change Potential (CC, kg CO_2 eq), Ecotoxicity for Freshwater (Eco-F, CTUe), Particulate Matter Formation (PM, disease inc.), Marine Eutrophication (EM, kg N eq), Freshwater Eutrophication (EF, kg P eq), Terrestrial Eutrophication (ET, mol N eq), Human Toxicity—Cancer (HTC, CTUh), Human Toxicity—Non-Cancer (HTnC, CTUh), Ionizing Radiation (IR, kBq U-235 eq), Land Use (LU, Pt), Ozone Depletion (OD, kg CFC – 11 eq), Photochemical Ozone Formation (POF, kg NMVOC eq), Resource Use—Fossils (RUF, MJ), Resource Use—Minerals and Metals (RUMM, kg Sb eq), and Water Use (WU, m^3 depriv.).

redistribution activities). Credits are associated with the phases "Product at retail" (the environmental impacts of production and distribution avoided through recovery) (Casson et al., 2024; Sundin et al., 2022), and "Avoided waste". Conversely, environmental debts are attributed to the operational phases, including "Collection," "Storage: Energy," "Storage: Waste," and "Redistribution." The contributions of each life cycle phase to the overall impact are detailed in Table 3.

3.2.1.1. Environmental credits. As proposed in Fig. 3a, the "Product at retail" shows the highest credit values in all impact categories, with the highest credit in the categories Ionizing Radiation (IR), Ozone Depletion (OD), Land use (LU), and Water use (WU), which are the main environmental impacts categories related to food production, as the products themselves are derived from field stages. On average, one food hub in a year saves 107 t of Carbon Dioxide Equivalent (CO_2 eq) Climate Change (CC), 3.19×10^{-5} m^3 deprived WU and 7.06×10^6 Points (Pt) LU. The

Table 3
Balance of the environmental assessment related to the different phases of the product life cycle identified as credits and debts as per the functional unit.

Impact Category	ACID	CC	Eco-F	PM	EM	EF	ET	HTC	HTnC	IR	LU	OD	POF	RUF	RUMM	WU
Unit of measure	mol H+ eq	kg CO2 eq	CTUe	disease inc.	kg N eq	kg P eq	mol N eq	CTUh	CTUh	kBq U-235 eq	Pt	kg CFC11 eq	kg NMVOC eq	MJ	kg Sb eq	m3 depriv.
Product at retail	-1.43×10^{3}	-1.06×10^{5}	-2.26×10^{6}	-1.06×10^{-2}	-5.18×10^{2}	-2.02×10^{1}	-5.87×10^{3}	-9.75×10^{-5}	-2.39×10^{-3}	-3.00×10^{4}	-7.15×10^{6}	-1.25×10^{-2}	-3.43×10^{2}	-1.36×10^{6}	-5.49×10^{-1}	-3.24×10^{5}
Avoided waste	-8.17×10^{1}	-9.51×10^{3}	-3.08×10^{5}	-8.34×10^{-4}	-1.33×10^{1}	-6.32×10^{-1}	-3.65×10^{2}	-2.88×10^{-6}	-6.62×10^{-5}	-1.26×10^{2}	-2.12×10^{4}	-8.67×10^{-5}	-4.03×10^{1}	-5.72×10^{4}	-7.21×10^{-3}	-3.25×10^{2}
Total credits	-1.51×10^{3}	-1.15×10^{5}	-2.57×10^{6}	-1.14×10^{-2}	-5.32×10^{2}	-2.08×10^{1}	-6.24×10^{3}	-1.00×10^{-4}	-2.45×10^{-3}	-3.01×10^{4}	-7.17×10^{6}	-1.26×10^{-2}	-3.84×10^{2}	-1.41×10^{6}	-5.57×10^{-1}	-3.24×10^{5}
Collection	6.23×10^{0}	1.98×10^{3}	7.89×10^{3}	1.13×10^{-4}	1.93×10^{0}	1.65×10^{-1}	2.09×10^{1}	9.52×10^{-6}	1.53×10^{-5}	2.60×10^{1}	1.08×10^{4}	2.99×10^{-5}	8.38×10^{0}	2.69×10^{4}	8.47×10^{-3}	1.16×10^{2}
Storage: Energy	1.32×10^{1}	3.11×10^{3}	9.00×10^{3}	6.57×10^{-5}	2.03×10^{0}	6.66×10^{-1}	2.32×10^{1}	1.31×10^{-6}	4.48×10^{-5}	3.94×10^{2}	1.52×10^{4}	7.32×10^{-5}	9.68×10^{0}	4.80×10^{4}	3.55×10^{-2}	1.97×10^{3}
Storage: Waste	1.51×10^{1}	1.15×10^{3}	2.57×10^{4}	1.14×10^{-4}	5.32×10^{0}	2.08×10^{-1}	6.24×10^{1}	1.00×10^{-6}	2.45×10^{-5}	3.01×10^{2}	7.17×10^{4}	1.26×10^{-4}	3.84×10^{0}	1.41×10^{4}	5.57×10^{-3}	3.24×10^{3}
Redistribution	8.46×10^{0}	2.41×10^{3}	1.95×10^{4}	1.11×10^{-4}	2.24×10^{0}	3.20×10^{-1}	2.36×10^{1}	2.01×10^{-6}	2.67×10^{-5}	6.46×10^{1}	1.18×10^{4}	5.88×10^{-5}	1.05×10^{1}	3.19×10^{4}	2.48×10^{-2}	2.01×10^{2}
Total debts	4.31×10^{1}	8.66×10^{3}	6.21×10^{4}	4.04×10^{-4}	1.15×10^{1}	1.36×10^{0}	1.30×10^{2}	1.38×10^{-5}	1.11×10^{-4}	7.86×10^{2}	1.10×10^{5}	2.88×10^{-4}	3.24×10^{1}	1.21×10^{5}	7.43×10^{-2}	5.53×10^{3}
Balance	$\mathbf{-1.47 \times 10^{3}}$	$\mathbf{-1.07 \times 10^{5}}$	$\mathbf{-2.51 \times 10^{6}}$	$\mathbf{-1.10 \times 10^{-2}}$	$\mathbf{-5.20 \times 10^{2}}$	$\mathbf{-1.95 \times 10^{1}}$	$\mathbf{-6.11 \times 10^{3}}$	$\mathbf{-8.65 \times 10^{-5}}$	$\mathbf{-2.34 \times 10^{-3}}$	$\mathbf{-2.94 \times 10^{4}}$	$\mathbf{-7.06 \times 10^{6}}$	$\mathbf{-1.23 \times 10^{-2}}$	$\mathbf{-3.51 \times 10^{2}}$	$\mathbf{-1.29 \times 10^{6}}$	$\mathbf{-4.82 \times 10^{-1}}$	$\mathbf{-3.19 \times 10^{5}}$

Note: Acidification Potential (ACID, mol H^{+} eq), Climate Change Potential (CC, kg CO_2 eq), Ecotoxicity for Freshwater (Eco-F, CTUe), Particulate Matter Formation (PM, disease inc.), Marine Eutrophication (EM, kg N eq), Freshwater Eutrophication (EF, kg P eq), Terrestrial Eutrophication (ET, mol N eq), Human Toxicity—Cancer (HTC, CTUh), Human Toxicity—Non-Cancer (HTnC, CTUh), Ionizing Radiation (IR, kBq U-235 eq), Land Use (LU, Pt), Ozone Depletion (OD, kg CFC − 11 eq), Photochemical Ozone Formation (POF, kg NMVOC eq), Resource Use—Fossils (RUF, MJ), Resource Use—Minerals and Metals (RUMM, kg Sb eq), and Water Use (WU, m^3 depriv.).

phase "Avoided waste", which accounts for the disposal of surplus food that would otherwise enter waste management systems, contributes 9.5 t of CO_2 equivalent savings annually. This phase has positive effects in all impact categories, but the greatest positive effects are obtained in the impact categories Eco-F and POF with values 3.08 × 105 CTUe and 40.3 kg NMVOCeq, as depicted in Fig. 3a and quantified in Table 3.

3.2.1.2. Environmental debts. As depicted in Fig. 3b, operational activities after donation introduce environmental debts. Among these, the "Collection" phase contributes approximately 18 % of total environmental debts, largely due to fossil fuel consumption for transportation. This phase has the greatest impact on categories such as Human Toxicity (Cancer and Non-Cancer effects), Particulate Matter (PM), Photochemical Ozone Formation (POF), and Climate Change (CC). The "Redistribution" phase accounts for 21 % of total environmental debts, with impacts distributed relatively evenly across the categories. The main environmental impact contributions come from energy consumption within the hubs (Storage: Energy) and the small fraction of wasted products (Storage: Waste), which account respectively for 30 % and 31 % of total flows.

3.2.1.3. Consolidated assessment. Fig. 3c shows the consolidated environmental impact assessment with a positive net impact of the activity related to the average food hub. From the results, the overall balance indicates a net production of environmental credits, i.e. the environmental debits generated by recovery and redistribution activities do not offset the potential environmental credits generated from the activities. Specifically, the total net credits in the CC category amount to 107 t of CO_2 equivalent annually. The "Product at retail" phase is the primary contributor to this result, preventing approximately 106 t of CO_2 equivalent emissions per year. In contrast, operational phases generate a comparatively small debt of 0.8 t of CO_2 equivalent.

As a sensitivity analysis, the environmental performance of food recovery and redistribution was evaluated under varying displacement scenarios. A full displacement factor (100 %) assumes that each kg of recovered food fully replaces an equivalent quantity of newly produced food. However, in practice, such one-to-one substitution may not occur (Sundin et al., 2023). Recent studies have demonstrated that displacement rates are partial and context-dependent, with values ranging between 40 % and 60 % depending on product characteristics, market conditions, and socioeconomic factors (Yang et al., 2024). To reflect this variability, we modelled five substitution scenarios: 100 % (ideal case of complete replacement), 75 % (high substitution), 50 % (average), 25 % (low substitution), and 0 % (null substitution, assuming donated food is entirely additional). The influence of varying displacement on the environmental performance of food redistribution is illustrated in Table 4 and Fig. 4.

The sensitivity analysis shows that for the majority of impact categories, including climate change, acidification, marine eutrophication, particulate matter formation, and photochemical ozone formation, the redistribution system provides a net environmental benefit across all displacement levels, including the most conservative scenario of null substitution. This outcome is largely attributable to the significant environmental credits associated with avoided waste treatment. However, a subset of impact categories becomes environmentally burdensome when displacement is very low. Specifically, eutrophication of freshwater, human toxicity (cancer and non-cancer), ionizing radiation, land use, resource use (fossil, minerals, and metals), and water use show unfavourable performances under the 0 % scenario (null substitution). Break-even analyses reveal that these categories require only modest substitution thresholds, ranging from approximately 1 % to 12 %, to result in a net environmental benefit.

3.2.2. *Economic assessment*

The economic analysis evaluated the financial sustainability of the

Table 4
Environmental impacts across 16 categories under varying displacement assumptions (100 % to 0 %) as per the functional unit.

Impact Category	ACID	CC	Eco-F	PM	EM	EF	ET	HTC	HTnC	IR	LU	OD	POF	RUF	RUMM	WU
Displacement factor	mol H+ eq	kg CO2 eq	CTUe	disease inc.	kg N eq	kg P eq	mol N eq	CTUh	CTUh	kBq U-235 eq	Pt	kg CFC11 eq	kg NMVOC eq	MJ	kg Sb eq	m3 depriv.
1.00	-1.4×10^{3}	-11×10^{4}	-251×10^{4}	-110×10^{-4}	-5.20×10^{2}	-19×10^{0}	-6.1×10^{3}	-8.6×10^{-5}	-23.4×10^{-4}	-3×10^{4}	-706×10^{4}	-123×10^{-4}	−351.2	-129×10^{4}	-4.8×10^{-1}	-31.8×10^{4}
0.75	-1.1×10^{3}	-8×10^{4}	-194×10^{4}	-84×10^{-4}	-3.91×10^{2}	-14×10^{0}	-4.6×10^{3}	-6.2×10^{-5}	-17.4×10^{-4}	-2.1×10^{4}	-528×10^{4}	-92×10^{-4}	−265.4	-95×10^{4}	-3.4×10^{-1}	-23.7×10^{4}
0.50	-7.49×10^{2}	-5×10^{4}	-138×10^{4}	-57×10^{-4}	-2.61×10^{2}	-9×10^{0}	-3.1×10^{3}	-3.7×10^{-5}	-11.4×10^{-4}	-1.4×10^{4}	-349×10^{4}	-61×10^{-4}	−179.5	-61×10^{4}	-2.1×10^{-1}	-15.6×10^{4}
0.25	-3.91×10^{2}	-3×10^{4}	-81×10^{4}	-31×10^{-4}	-1.31×10^{2}	-4×10^{0}	-1.7×10^{3}	-1.3×10^{-5}	-6×10^{-4}	-6.8×10^{3}	-170×10^{4}	-29×10^{-4}	−93.7	-28×10^{4}	-703×10^{-4}	-7.5×10^{4}
0.00	-3.3×10^{1}	-8.5×10^{2}	-25×10^{4}	-4×10^{-4}	-2×10^{0}	7.27×10^{-1}	-235×10^{0}	1.09×10^{-5}	4.51×10^{-5}	659.13	8.8×10^{4}	2×10^{-4}	−7.9	6.3×10^{4}	671×10^{-4}	5.2×10^{4}
Linear regression-Slope (S)	-1.4×10^{3}	-11×10^{4}	-226×10^{4}	-106×10^{-4}	-518×10^{0}	-20×10^{0}	-5.8×10^{3}	-9.7×10^{-5}	-24×10^{-4}	-3×10^{3}	-715×10^{4}	-125×10^{-4}	−343.3	-136×10^{4}	-5.4×10^{-1}	-32×10^{4}
Linear regression-Intercept (I)	-33×10^{0}	-850×10^{0}	-25×10^{4}	-4×10^{-4}	-2×10^{0}	7.27×10^{-1}	-235×10^{0}	1.09×10^{-5}	4.51×10^{-5}	6.5×10^{2}	8.8×10^{4}	2×10^{-4}	−7.9	6.3×10^{4}	671×10^{-2}	5.2×10^{4}
Ratio (-I/S)	−2 %	−1 %	−11 %	−4 %	−1 %	4 %	−4 %	11 %	2 %	2 %	1 %	2 %	−2 %	5 %	12 %	2 %

Note: Acidification Potential (ACID, mol H^+ eq), Climate Change Potential (CC, kg CO_2 eq), Ecotoxicity for Freshwater (Eco-F, CTUe), Particulate Matter Formation (PM, disease inc.), Marine Eutrophication (EM, kg N eq), Freshwater Eutrophication (EF, kg P eq), Terrestrial Eutrophication (ET, mol N eq), Human Toxicity—Cancer (HTC, CTUh), Human Toxicity—Non-Cancer (HTnC, CTUh), Ionizing Radiation (IR, kBq U-235 eq), Land Use (LU, Pt), Ozone Depletion (OD, kg CFC-11 eq), Photochemical Ozone Formation (POF, kg NMVOC eq), Resource Use—Fossils (RUF, MJ), Resource Use—Minerals and Metals (RUMM, kg Sb eq), and Water Use (WU, m^3 depriv.)

hubs by comparing the economic value of recovered food to the costs of recovery and redistribution operations (Sundin et al., 2023). Table 5 provides detailed data on the economic value of recovered products and operational costs.

3.2.2.1. Economic benefits. The analysis of recovered products shows that, on average, one hub in one year manages to recover an equivalent value of 336,109 € in food products. This is representative of the value of resources involved in the production and distribution of the products that are diverted from waste and recovered. The highest share of the economic credits is made up by the fruit and vegetables category (39.14 %), followed by bread (21 %) and cooked food (10.75 %). Additional savings of 8448 € per year are attributed to avoided waste management costs.

3.2.2.2. Economic costs. The operational costs required for collection, storage, and redistribution averaged 28,226.18 € annually per hub. Analyzing the composition of this amount, the bulk is related to the cost of the driver that performs the collection activities (56.68 %), while energy consumed at the hub level amounts to 12.45 % and transportation costs (fuel, vehicle depreciation, insurance) related to collection and redistribution amount to 18.83 % and 12.04 % respectively.

3.2.2.3. Overall balance. The comparison between economic benefits and operational costs reveals a highly favorable balance. On average, one hub generates a net yearly economic surplus (generated benefits net of operational costs) of 316,331 €, corresponding to benefits to costs ratio to the total costs is 11.91, which increases to 12.21 if savings in waste management savings are also taken into account. These results underscore the significant economic efficiency of food hubs, highlighting their capacity to deliver substantial financial benefits while incurring low operational costs.

3.2.3. Social assessment

The social assessment evaluates the impact of food hubs in addressing food insecurity, focusing on three key indicators: the total number of redistributed meals, the number of beneficiaries served, and the average number of meals provided per beneficiary.

On average, one hub in a year manages to redistribute 69.7 t of surplus food, net of any waste generated after donation (Table 6). This amount corresponds to approximately 139,395 meals per year. These redistributed meals represent a critical resource for addressing food insecurity suffered by vulnerable urban citizens. On average, each hub supports 3000 beneficiaries annually, providing about 46.5 meals per person over the year. With hubs operating for 46 weeks annually, this equates to more than one meal per week for each beneficiary. These results underscore the tangible and sustained impact of food hubs in improving access to nutritious food for low-income and underserved communities.

4. Discussion of results and limitations

This study comprehensively assesses for the first time the sustainability impacts of food redistribution in urban areas through food hubs. Results show that they generate at the same time net environmental, social and economic benefits, quantitatively assessing them.

Table 7 reports the key sustainability indicators adopted to measure hubs' impact, underscoring their environmental, economic and social sustainability performance. For a more tangible representation of the consequent benefits, it is possible to normalize environmental and economic credits for each meal, thus approximately 0.76 kg of CO_2 equivalent and 2.27 €. Fig. 5 provides an overview of the social, economic, and environmental dimensions of food recovery and redistribution through food hubs. It highlights the balance in percentage over the total dimensional impact in terms of quantity (meal composition),

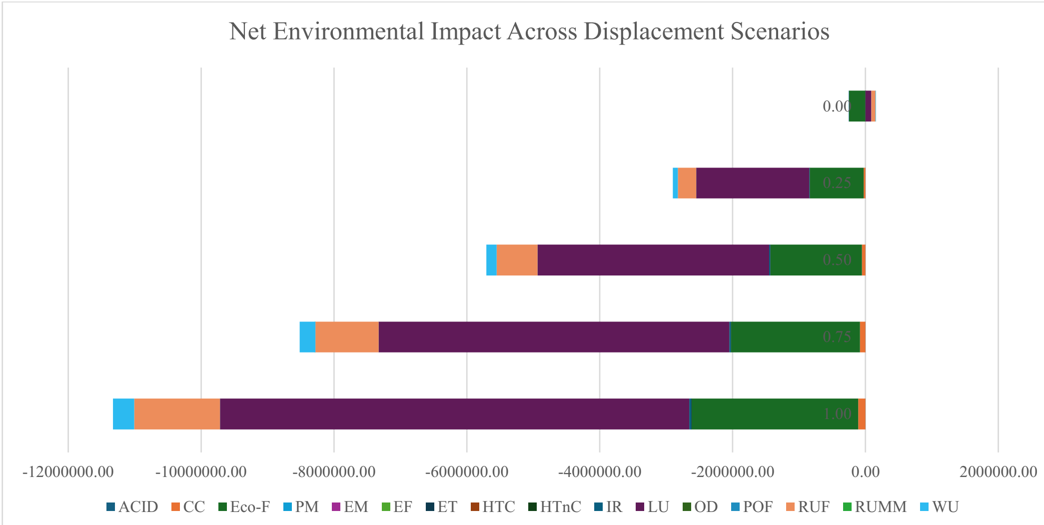

Fig. 4. Net environmental impacts associated with food recovery and redistribution from the food hub under five displacement scenarios (100 %, 75 %, 50 %, 25 %, and 0 %).

Table 5
Economic impact assessment expressed per functional unit. The last row reports the overall balance (benefits minus costs).

		2022		2023		2024	
		Isola	**Lambrate**	**Isola**	**Lambrate**	**Isola**	**Lambrate**
Benefits							
Product class	**Unit of measure**						
Various dry	€	7704.40	7286.57	8115.12	7123.48	5034.82	2218.00
Bread	€	76,559.56	72,407.60	56,128.10	67,700.48	42,862.62	49,082.27
Bakery	€	32,898.00	31,113.89	26,860.96	33,762.96	17,295.60	17,652.88
Fruit & vegetables	€	138,573.81	131,058.72	86,890.50	168,794.28	81,117.50	73,293.07
Meat	€	32,131.13	30,388.60	30,342.08	23,641.85	24,270.27	11,982.28
Fish	€	1445.71	1367.30	2056.98	202.33	1028.49	505.82
Cooked food	€	40,315.33	38,128.96	14,363.71	33,563.27	9114.40	51,072.98
Dairy	€	31,453.95	29,748.15	37,686.27	18,858.23	21,116.63	10,241.29
A. Total	€	361,081.88	341,499.79	262,443.72	353,646.90	201,840.33	216,048.59
Avoided cost category							
Waste management avoided unitary costs	€/kg	0.12	0.12	0.12	0.12	0.12	0.12
B. Waste management avoided costs	€	8999.16	8511.12	6375.00	9610.92	5261.76	4891.08
Costs							
Cost category	**Unit of measure**						
Collection – Unitary vehicle cost	€/km	0.36	0.36	0.36	0.36	0.36	0.36
Distances covered	Km	14,640	14,880	14,640	14,880	8540	8680
C. Collection– Vehicle cost	€	5270.40	5356.80	5270.40	5356.80	3074.40	3124.80
D. Collection – Driver cost	€	16,000	16,000	16,000	16,000	9333	9333
Storage – Unitary electricity costs	€/kWh	0.7	0.7	0.38	0.38	0.37	0.37
Electricity consumption	kWh	7008	7008	7008	7008	4088	4088
E. Storage – Electricity cost	€	4905.60	4905.60	2663.04	2663.04	1512.56	1512.56
Redistribution – Unitary vehicle cost	€/km	0.45	0.45	0.45	0.45	0.45	0.45
Distances covered	Km	6730	8369	6730	8369	3926	4882
F. Redistribution-Vehicle cost	€	3028.50	3766.05	3028.50	3766.05	1766.63	2196.86
TOTAL COSTS	€	29,204.50	30,028.45	26,961.94	27,785.89	15,686.92	16,167.56
Economic balance (A + B-C-D-*E*-F)	€	**340,876.54**	**319,982.46**	**241,856.78**	**335,471.93**	**191,415.17**	**204,772.11**

economic value, and environmental benefit for different food categories, underlining the role of each food category in the redistribution system. In terms of mass, fruit and vegetables constitute the main component of recovered food, accounting for 63 % of the total, followed by bread and bakery products (20 %) and, to a lesser extent, dairy products, meat and fish, and dry goods or cooked food products. However, the economic value recovered does not follow the same distribution. Although fruit and vegetables continue to be an important category, bread and bakery products make the largest economic contribution, while meat and fish, despite having a smaller volume, contribute significantly due to their high unit costs. From an environmental point of view, recovered meat and fish generate the greatest savings in terms of CO_2 equivalent, given the intensity of emissions associated with their production, followed by fruit and vegetables and dry goods, and cooked food products. While each dimension is assessed separately using specific appropriate indicators, their joint consideration in Fig. 5 allows us to underline how different food categories contribute unevenly to the three pillars of sustainability, highlighting synergies and trade-offs for impact evaluation. Comprehensive sustainability assessments of surplus food redistribution remain scarce (Hecht and Neff, 2019; Sundin et al., 2023). The choice to conduct a multi-dimensional assessment that comprehensively includes the three pillars of environmental, social, and economic sustainability is based on the recognition that surplus food redistribution affects all three areas of sustainability – mitigating environmental

Table 6
Social impact assessment expressed per functional unit.

	2022		2023		2024	
	Isola	Lambrate	Isola	Lambrate	Isola	Lambrate
						Product class
Dry/various	1608	1521	1694	1487	1051	463
Bread	13,159	12,445	9647	11,636	7367	8436
Bakery	2026	1916	1654	2079	1065	1087
Fruit and vegetables	46,879	44,337	29,395	57,103	27,442	24,795
Meat	3784	3578	3573	2784	2858	1411
Fish	86	81	122	12	61	30
Cooked food	2243	2121	799	1867	507	2841
Dairy	5209	4926	6241	3123	3497	1696
Total	74,993	70,926	53,125	80,091	43,848	40,759
Waste	750	709	531	801	438	408
Net redistributed	74,243	70,217	52,594	79,290	43,410	40,351
Equivalent meals	148,486	140,433	105,188	158,580	86,819	80,703
Beneficiaries	3800	2200	3800	2200	3800	2200
Meals per beneficiary	39.01	63.83	27.64	72.08	22.81	36.68

Table 7
Summary of main environmental, economic and social sustainability indicators. Every indicator is expressed per functional unit.

Sustainability dimension	Key indicators
Environmental	107 t of CO_2 eq credits Positive outcomes across all categories of environmental impact
Economic	336,109 € in redistributed food products 316,331 € in net economic value generated The ratio between economic value recovered and total costs equal to 11.91 (12.21 when including savings in waste management costs)
Social	More than 3000 beneficiaries served 69.7 t recovered, equivalent to 139,395 meals redistributed (46.5 per beneficiary)

impacts (through avoided production and waste), delivering nutritional and social value to vulnerable populations, and generating economic value by recovering food that would otherwise be lost.

The results provide significant implications for nonprofit, private organizations and policymakers involved in the recovery and redistribution of surplus food in urban areas. First, they demonstrate through a multi-dimensional assessment the sustainability impacts of neighborhood food hubs as an effective instrument to perform urban recovery and redistribution of surplus food. The study represents a first-of-a-kind assessment of the innovative redistribution model of food hubs, a prominent policy instrument to tackle food waste and food insecurity, whose evaluation is still lacking (Bartezzaghi et al., 2025; Bartezzaghi et al., 2022; Casson et al., 2024). While on one side the results consolidate the literature (Bergström et al., 2020; Casson et al., 2024; Sundin et al., 2023) that demonstrates that recovery and redistribution systems provide high environmental savings, on the other they provide for the

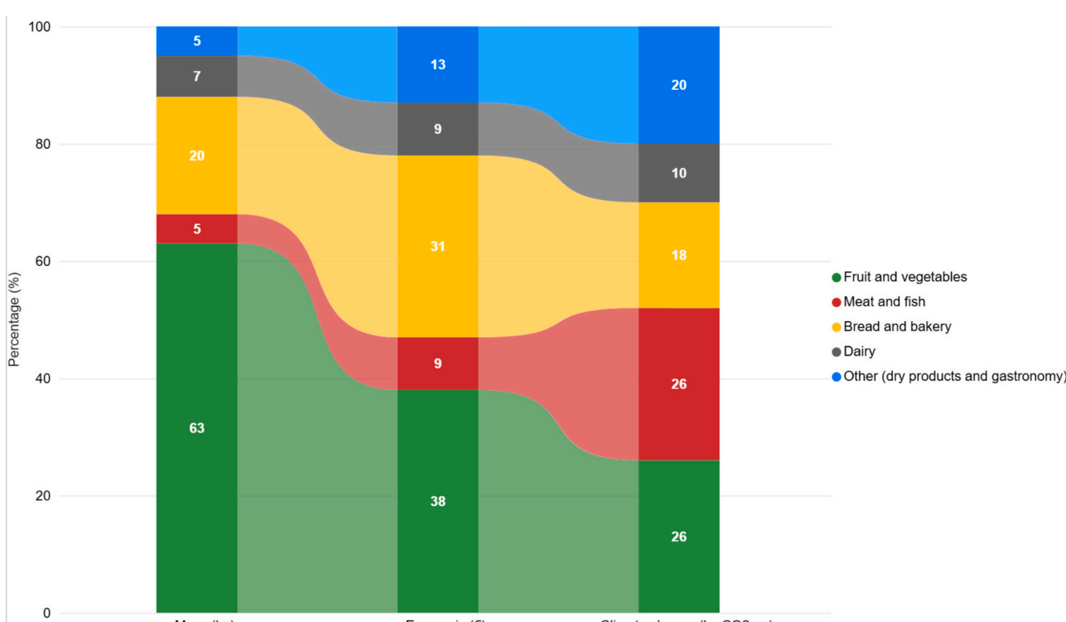

Fig. 5. Recovered and redistributed food from the food hubs: Meal composition, recovered economic value, contribution to climate change for each aggregated food category as per functional unit.
The first part of the graph shows the distribution in terms of mass, showing the percentage composition of an average meal. The second part shows the percentage contribution of each aggregated food category regarding the economic credits recovered. The third part shows the environmental credits for each aggregated food category, referring to Climate Change only. Percentages are rounded to the closest integer value.

first time a holistic assessment of their sustainability impacts as well as unpacking the incidence of different product categories and process phases on these impacts. Indeed, the study shows a high incidence of fresh food (e.g., fruit, vegetables, animal proteins, bread and bakery) within recovered and redistributed food products, showing the capability of food hubs to deliver adequate and nutritionally balanced meals and overcome a traditional weakness of food banking (Bartezzaghi et al., 2025; Bartezzaghi et al., 2022; Irwin et al., 2007). Secondly, they allow to analyse and pinpoint the impact of individual activities and product categories in the environmental and economic sustainability of such model, allowing further optimization actions around food hubs, i.e. prioritizing those products whose recovery bring the highest environmental benefits, exchanging products between food hubs to enhance the nutritional balance of redistributed food, or working to enhance the economic or environmental sustainability of certain activities (such as using e-bikes or electric vehicles).

Third and most importantly, the quantification of the positive sustainability impacts of food hubs allows this study to contribute to the debate on the long-term financial sustainability of food redistribution activities (Mousa and Freeland-Graves, 2017; Papargyropoulou et al., 2024; Trejo-Pech et al., 2023). Indeed, the results of the economic analysis show that food hubs recover a value that is more than 11 times the cost of their operations. However, their operations rely on volunteer work and sporadic funding from private and public sponsorships, which underscores the importance of implementing support schemes that recognize their positive impacts on communities and the environment to stabilize their operations. This recovered economic value is not captured by food hubs, i.e. it does not allow them to directly sustain their operations. Nonprofit organizations managing food hubs rely on periodic external funding to cover operational costs, a model that presents challenges to their long-term stability. Securing steady financial resources is critical to sustaining these essential services (Papargyropoulou et al., 2024). Policymakers and food system stakeholders should acknowledge the multidimensional benefits brought by food hubs to local communities and the environment through their continued contribution to urban food security and mitigation of environmental impacts of food waste, potentially opening pathways to innovative financing mechanisms, such as public funding or environmental impact bonds.

While literature generally recognizes the social and environmental benefits of food recovery and redistribution (Papargyropoulou et al., 2014; Sundin et al., 2023), it also highlights possible trade-offs between the social and environmental dimensions, e.g. where social benefits (enhancement of food and nutrition security) generate rebound effects and limit environmental benefits (Hegwood et al., 2023). Through sensitivity analyses, we have shown that the environmental benefits across all dimensions also hold with very low degrees of displacement. We recognize, nonetheless, that the overall sustainability benefits of food redistribution are mediated by demand elasticity and socioeconomic constraints. If demand is elastic, freely available food may induce sizeable rebound effects through additional consumption that offsets environmental gains from waste reduction or avoided additional production (Hegwood et al., 2023; Sundin et al., 2022). While demand for food products tends to be relatively inelastic (Andreyeva et al., 2010), future studies could enhance the impact evaluation of food hubs through either primary data on actual production and consumption patterns or more sophisticated economic analysis based on real-world price elasticities. Other socioeconomic and logistical constraints (such as inefficient redistribution, inadequate infrastructure, or social stigma around redistributed food) can reduce the realized economic, social, and environmental benefits (Millar et al., 2020). Nonetheless, food recovery and redistribution still greatly outperforms alternative recovery options such as anaerobic digestion (Papargyropoulou et al., 2014; Sundin et al., 2023), while delivering sizeable social benefits in terms of food and nutrition security enhancements.

Our results are derived in a specific context, which may hamper broader generalizability. However, this study aims to offer a foundational tool for replicating the assessment in other settings, contributing to a broader understanding of food redistribution systems' policy implications and enabling their optimization on a global scale. While Milan's strong institutional support and food policy infrastructure is an important feature, as also highlighted in recent literature (Bartezzaghi et al., 2025; Eriksson et al., 2015; Laurent et al., 2014; Papargyropoulou et al., 2024), the model relies on a clear and well-defined and formalized set of resources, actors and capabilities, and on a relatively straightforward and simple operational model, designed to be easily replicable in other urban contexts (Bartezzaghi et al., 2025). Its simple operational model is in principle replicable by any third sector organization with the necessary capabilities in terms of handling perishable food items. The only necessary conditions to properly replicate are a basic regulatory framework for food safety, logistic capabilities, and the availability of a network of donors and receivers. These conditions are easily found in medium-high income settings, while they may be more challenging in lower-income countries. Future research could test the validity of these findings in contexts lacking strong local government leadership or outside urban contexts.

Furthermore, as with all LCAs, results are subject to methodological assumptions and uncertainties (Lucas et al., 2023). To mitigate these, the study employed reliable databases and relied on primary data to enhance robustness. The main limitations regarding data concern the upstream phases of food production and distribution as well as the availability of detailed product information. It was not possible to collect precise information on the origin of products; therefore, the general market for Europe datasets in the Ecoinvent database were used for the average European products, including transportation. Furthermore, it was not possible to obtain detailed data for each individual product recovered, therefore the analysis is performed in product categories. The system boundaries were defined to end at the point of food delivery to beneficiaries, excluding potential waste generated at the consumer level. However, given the nature of the service (urgent food assistance), the likelihood of significant waste is minimal. Additionally, the study does not account for potential costs borne by retailers for sorting and donating surplus food, which could offset savings from reduced waste management fees. While existing literature suggests these costs can be significant, non-monetary incentives, such as enhanced reputation, may act as a non-monetary reward and compensate for such costs (Sert et al., 2018).

5. Conclusions

In conclusion, the study has, for the first time, demonstrated the sustainability performance of food hubs in urban areas. The evaluation of environmental, economic, and social impacts shows a favorable performance across all three dimensions. Environmentally, the recovery and redistribution activities result in a net production of 107 t of CO_2 equivalent credits annually, indicating a positive environmental outcome. Modelling several levels of displacement factor shows that food hubs remain environmentally beneficial even with low substitution. However, impacts like land and water use are more sensitive, reinforcing the need to minimise rebound effects and improve actual food replacement. Through their localized model for surplus food recovery and redistribution, connecting local retailers to food aid organizations, food hubs recover a significant economic value compared to their operational costs. The hubs generate a net annual surplus of 316,331 €, with a benefits-to-costs ratio of 12.21. Socially, each hub redistributes an average of 69.7 t of surplus food per year, equating to approximately 139,395 meals, thereby contributing to food security for underprivileged citizens and reducing waste. To ensure the sustainability of food hubs, policymakers may consider implementing support schemes that recognize their positive impacts on communities and the environment. Private actors and sponsors should consider offering stable funding and resources to address operational challenges. Future studies could extend the system boundaries to mitigate rebounds effects and explore broader applications of the food hub model in different urban contexts and investigate ways to improve food collection logistics.

Declaration of competing interest

The authors declared no actual or potential conflicts of interest with respect to the research, authorship, and publication of this article.

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Data availability

The authors do not have permission to share data.

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