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Abstract

Significant food waste occurs during distribution due to inefficiencies in handling, storage, and logistics. This research investigates food waste in the distribution sector, focusing on quantification and valorization, through three systematic literature reviews and a case study. The first review analyzes food waste quantification in large-scale retail, revealing inconsistent recording methods across supermarkets, which prevent data comparison and the estimation of the average value of waste. The second review examines the catering sectors: hospital canteens (comparing two preparation methods, one of which generates less waste), school canteens (with comparable data), and restaurants (where consumer waste exceeds kitchen waste). The third review explores food waste valorization strategies, classified according to the European Commission's waste hierarchy: prevention, human consumption (donation), feed, material recycling, nutrient and energy recovery, and disposal. Donation, although a priority after prevention, is not always the best option from an environmental point of view. The case study focuses on a food donation service where supermarkets' unsold food is collected, stored in a hub, and converted into meals for people in need. Using Life Cycle Assessment (LCA), the service was shown to have significant environmental benefits—up to 99% reductions in Global Warming Potential and Acidification—due to the avoided impacts of food waste. Socially, it provided 73,493.1 kg of food, enabling daily meals for 134 people. This work highlights the complexity of food waste quantification and the potential of donation strategies in achieving both environmental and social benefits in the distribution sector.

Keywords Food distribution sector; food donation; food waste; LCA; quantification; valorization.

Introduction

Food loss and food waste have always been a problem that should not be underestimated. Food and Agriculture Organization (FAO) in 2011 has estimated that, of all the food produced globally, i.e. 1.3 billion tons, one-third is lost or wasted every year, and it associated it with a total carbon footprint of 4.4 Gt CO_2-eq per year (FAO, 2015), due to both its management and FSC embedded impacts resulting in 2.31 trillion euros of societal cost (FAO, 2014; Vandermeerscha *et al.*, 2014; García-Herrero *et al.*, 2019; Arias *et al.*, 2022). These data show that food waste is negative from different points of view: it has an environmental impact, an economic impact, and also a social impact, which is often underestimated or even not considered at all. This final point is crucial; in fact, a large number of people continue to suffer from malnutrition or undernutrition, to the extent that the Sustainable Development Goal 2 (zero hunger) seeks to eradicate hunger, attain food security, and enhance nutrition (United Nations, 2015).

Waste occurs in every stage of the supply chain, and it is not always easy to reduce it, but among all the stages, the retail one has the biggest potential for reducing food waste. According to European Commission estimates, obtained by extrapolating Eurostat data, in the EU 27 4.4 million tons of food are discarded at the retail stage, which represents approximately 5% of total food waste (Cicatiello *et al.*, 2016). However, studying the retail sector is very important because some studies suggested that, contrarily to what happens in other steps of the chain, a significant share of the products considered unsalable by the retailers is still perfectly suitable for human consumption and instead of being wasted they can be donated or sold at a discount (Cicatiello *et al.*, 2017).

It is important to consider that not all foods have the same environmental impact, for instance, among wasted food, cereals represent the largest amount, in mass, and Scherhaufer *et al*. (2018) attribute 25 million t CO_2 eq to their waste in Europe in 2011, but, they attribute around 56 million t CO_2 eq to beef waste, even though the amount of cereal waste reported is almost twenty times higher than bovine meat waste. This is because the environmental impact of animal food waste is much higher than the impact of cereal waste (Damiani *et al.*, 2021).

The circular economy preserves the added value of products for as long as possible by ensuring that end-of-life products are transformed into other products with additional value (European Commission, 2020). In this perspective, the reduction of food waste and loss by recovering these substrates from other processes, in the form of Secondary Raw Material (SRM), would produce a reduction in the consumption of resources and raw materials, in the impacts and costs related to waste disposal (Cappelli *et al.*, 2019).

It is important to understand that food waste is not all the same. In some cases, food is no longer suitable for consumption, thus it has to be turned into different products (for instance compost); in other cases, it may no longer be consumed by humans but can still be used as animal feed; and, sometimes, it is, also, still suitable for human consumption (Cicatiello *et al.*, 2016).

The European Waste Framework Directive (WFD) ranks waste prevention and management options in order of priority in a waste hierarchy (European Commission, 2008; Eriksson *et al.*, 2017), and the Waste Framework Directive 2008/98/EC proposes the following waste management hierarchy (European Commission, 2008; Vandermeerscha *et al*., 2014):

- Prevention
- Preparing for re-use
- Recycling
- Recovery (e.g., energy recovery)
- Disposal

At the top of this hierarchy is "prevention" which includes strategies to reduce the surplus food. This means that the greatest efforts are to be placed on keeping edible food edible. Unfortunately, a world with a total absence of waste is utopian, so therefore it is necessary to consider the other categories.

The second-best way to valorize surplus food is donation, which basically means reusing this food for human consumption, but it is not always possible because, in order to be redistributed to humans, food must be conform to some safety and hygiene norms, due to its highly degradable nature. This factor can limit the quantity of reused food and by consequence increase food waste . Going down a step of the pyramid, the next food management method is to reuse food waste for animal consumption. Then the hierarchy proceeds with a less preferable solution: material recycling, which is followed by nutrient recovery and energy recovery. The very least preferable option, which should be avoided, if possible, is disposal.

The aim of this work is to quantify Italian food waste in the retail sector, specifically in the large-scale retailers, also referred as "La grande distribuzione organizzata" (GDO) and in food service, and to understand how to valorize it following the waste management hierarchy proposed by the Waste Framework Directive 2008/98/EC.

In this context, this study brings two main contributions to the current debate on food waste. First, it aims to broaden the analytical perspective by explicitly integrating the social dimension into the assessment of food waste valorization strategies, which are often limited to environmental evaluations. Second, the study highlights a critical data gap regarding the quantification of food waste in the Italian large-scale retail and food service sectors. This lack of reliable and standardized data not only prevents a full understanding of the phenomenon but also undermines the design of effective and targeted strategies. By combining these two perspectives, the inclusion of social impact and the identification of structural data weaknesses, this research proposes a more comprehensive and inclusive approach to food waste management.

Materials and Methods

To achieve the aim of this work, two distinct paths were adopted: three systematic bibliographic research were conducted, following the PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) statement: the first on the quantification of waste in supermarkets, the second on the quantification of waste in catering and the third on how to valorize such food waste in an LCA perspective. Furthermore, a case study was developed, in collaboration with the *On Foods* project and Banco Alimentare, which have activated several neighborhood hubs in Milan. In this case study, a single hub was analyzed both in terms of environmental impact, developing the LCA model related to the service offered by the hub, and in terms of social impact.

Systematic bibliographic research

To claim to have carried out systematic bibliographic research, at least three databases must have been consulted, always using the same search terms. For this work, the database used are "Science Direct", "Web of Science" and "Scopus". No restrictions were imposed.

The search keys used in the first bibliographic research are ""food waste" AND supermarkets AND quantification". Initially, 1130 results were found on ScienceDirect, 11 on Web of Science, and 6 on Scopus. After reading the titles and abstracts, 55, 3 and 3 articles were selected, respectively, excluding the remaining 1086. The last screening was performed both by reading the articles in their entirety, discarding 46 articles, and by eliminating duplicates (5) from the 15 remaining works. The works actually considered were 10: 9 from ScienceDirect and 1 from Web of Science, while Scopus did not provide any article used for this work. The second research used the following keys ""food waste" AND (hospitality OR restaurants OR school OR catering OR food service) AND quantification". ScienceDirect submitted 8383 articles, while Web of Science and Scopus submitted 168 and 51 respectively. After reading the titles and abstracts, and consequently discarding 8535 articles, the number of selected works was 34 for ScienceDirect, 23 for Web of Science and 10 for Scopus. The articles used in this work, after having made the last selection by reading them in full and eliminating both the ineligible ones (40) and the duplicates (14 articles), were 13. Specifically, 8 from ScienceDirect, 5 from Web of Science and, once again, none from Scopus. The keys of the last research are “LCA AND valorization AND “food waste” AND “circular economy””. The keywords of the last search are "LCA AND valorization AND "food waste" AND "circular economy". ScienceDirect offered 867 articles, Web of Science 21 and Scopus 16. The remaining results, after the screening based on reading the article and the abstract, were 139 from ScienceDirect, 5 from Web of Science and 6 from Scopus, with the exclusion of the remaining 754 papers. The articles considered after reading the full text, which discarded 115 articles, and the elimination of duplicates (8) are 27: 26 from ScienceDirect, only one from Web of Science and, as in the previous cases, always zero from Scopus.

Case study

Goal and scope definition

The Life Cycle Assessment (LCA) conducted on the service offered by the analyzed food hub was designed to evaluate the environmental impacts associated with the recovery of food from waste streams and its distribution to those in need. This work aims to provide information on the environmental impacts of this service, evaluating its benefit. The idea is to evaluate whether collecting food waste from supermarkets, bringing it to the “Bassini” hub, a neighborhood hub placed in via Bassini 26 in Milan, storing it there, and then redistributing it to the front-line NGO is more convenient, from an environmental point of view, than simply having the GDO send it to disposal. This valuation was done quantifying the positive and negative outcomes of this initiative by introducing and proposing an environmental credits and debits approach, utilizing the LCA tool. Moreover, the social impact of this solution is also considered.

Functional unit and reference flow

The functional unit in this study is defined as 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.

System boundaries

The study conducted has a 'cradle-to-gate' approach, where the 'cradle' represents the production of food, and the 'gate' corresponds to the moment when the recovered food is donated to the indigents (Figure 1). The processes included are:

- Product at retail: surplus food, packaging, distribution
- Avoided waste: avoided food waste for the municipal waste management system
- Collection: recovery of unsold food from supermarkets
- Quality screening: food found inedible after the screening managed as waste
- Storage: energy consumption at the hub
- Redistribution: surplus food redistribution to nonprofit organizations.

Data collection

The food hub managers have provided primary data directly for the environmental and social assessment. In addition to the number of beneficiaries reached in relation to the "Bassini" hub in Milan, these statistics also cover the food mass flows, recovery, and routes of excess food, as well as the collection (from donor retailers) and delivery points (front-line food aid nonprofit organizations). The recovered surplus food data are broken down into product classes and presented as weight.

Inventory modelling framework

Allocation method, temporal and geographical representativeness

In this work, a mass allocation criterion was employed. The analysis covers a period of 31 months: from January 2022 to July 2024 included and was carried out in the city of Milan and its province.

Inventory analysis

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

Product at retail

The food surpluses recovered during the period analyzed were recorded and divided into categories based on the type of food. All the products have an environmental impact related to the production, packaging and distribution activities. The impact of surplus recovered from the supermarkets was assessed using databases Ecoinvent v.3.10 and Agribalyse v.3.1, which offer datasets related to food products at retail level. The product at retail is included in the study as an environmental credit. This is because it is assumed that, in the absence of recovery and redistribution activities, a similar product, with the same environmental impact, would have been produced and distributed to provide the poor with the same product and nutritional value.

Avoided waste

Recovering food surpluses avoids them being managed as waste, and also avoids emissions related to their disposal. Therefore, this avoided waste represents an environmental credit.

Collection

In order to collect all the surplus food donated by 6 supermarkets in the city of Milan (Italy), a refrigerated truck was used, starting from the Banco Alimentare's depot in Muggiò (outskirts of Milan city), it passes daily, except for weekends, by all the supermarkets, arrives at the hub and finally returns to the depot in Muggiò. The route was optimized in order to travel the least possible number of kilometers, which is 44.2 km. The impact of this step of the service represents a debit: for each collection round, the corresponding emissions were calculated, considering the use of refrigerated transport. The data used for its calculation are presented in Table 1.

Quality screening

Approximately 1% of the donated food did not pass the hub's quality and safety checks, so, therefore, it becomes a waste that has to be managed through the municipal waste management system. Since the food waste is still packaged, also the packaging should be considered, therefore the Italian waste management scenario was selected (CONAI, 2024) as representative of the paper and plastic waste stream. Additionally, the impact also includes the 30-km ride that the waste collection trucks take to get to the disposal site. The impact of this step also represents a carbon debit.

Storage

The second step is the storage of donated food in the hub; for this purpose, the cold storage rooms were analyzed to know their annual consumption: 6912 kWh for meat conservation, and 6240 kWh for fruit and vegetable conservation (Table 1). In the environmental analysis, the Italian residual energy mix was considered, and the emissions resulted are an environmental debit.

Redistribution

For the redistribution, the route between each frontline NGO and the hub was calculated, back and forth, since the car that collects the donated food starts from the NGO, goes to the hub, picks up the food, and finally returns to the NGO where the products will be delivered to the beneficiaries. The average distance covered was calculated using 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. With this information and knowing frequency per week these NGO go to the hub to pick up the donated food, it was possible to calculate the environmental impact of this step of the service, which, again, represents a debt.

Environmental and social impact assessment (ESIA)

In accordance with the objective of the study, the results of the analysis are proposed following two sustainability categories: the environmental and social dimensions. The methodology used to assess the environmental sustainability of the new service is based on LCA, while the social sustainability impact assessment relies on indicators referring to the number of meals donated, and food-insecure people supported.

Environmental impact

SimaPro 9.6.0.1 (PRé Sustainability, Amersfoort, The Netherlands) and the databases Ecoinvent v 3.10 and Agribalyse v 3.1 were utilized to evaluate the environmental impact.

To ensure that waste flows that are avoided and those that remain in the system are clearly distinguished, a cut-off allocation criterion was followed for the analysis. Analyzing life cycle inventory data is necessary for the Life Cycle Impact Assessment (LCIA) phase in order to evaluate possible environmental impacts. This step entails associating particular environmental impact categories with pollutant flow data. Each life cycle stage's environmental effects, including the gathering, storing, and redistributing of recovered food, are then computed.

Table 2 shows the impact categories considered in the study, together with their units of measurement and the acronyms used to describe them.

Social impact

For the assessment of the social impact, knowing that, according to the Italian Reference Nutrient Intake Levels (LARN) (Società Italiana di Nutrizione Umana-SINU, 2014). Five hundred grams of food are identified as an equivalent dish, the number of equivalent meals distributed, the number of equivalent meals provided per beneficiary by the food hub and the number of people served were calculated and considered as indicators. This allowed for a quantitative assessment of the contribution to lowering food insecurity and helping those in need.

Limitations

Limitations of this study may be related to geographical and temporal representativeness. Considerations can only be made about the case study analyzed and the availability of the information collected. Moreover, the *On Foods* project includes several food hubs, but the findings are based solely on the case study of the "Bassini Hub". This hub was selected due to the higher availability and quality of collected data, which allowed for a more robust and coherent analysis. Including all hubs would have significantly increased the complexity and length of the study. As a consequence, the results should not be generalized without caution. While some insights may offer indications applicable to similar urban contexts or other hubs in the network, a critical evaluation of their scalability to different settings (e.g., rural areas, hubs with different operational models) is necessary. Further research should investigate whether the trends observed at the

Bassini Hub are consistent across other hubs and time periods within the *On Foods* project.

About the information on the origin of food products, some of this information could not be collected and, as a precaution, average global transport was attributed to these products. This choice derives from the aggregated nature of the data available in the Agribalyse database, from which all the items belonging to the relevant food category were considered, their associated environmental impacts were calculated, and a representative average was obtained for each food category. Consequently, a specific sensitivity analysis was not conducted in this regard. Nevertheless, the importance of such an analysis is recognized and, in future studies, with a more detailed and disaggregated data collection, it will be implemented to assess the effect of different assumptions regarding the origin and transport of products. Another limitation is that this study does not includes the economic impact of the service. However, it is important to note that the service is conceived as being based on voluntary donations, which implies that it does not start from a cost burden for the stakeholders involved. The economic model can be seen as analogous to an environmental credit approach: the service begins with a form of "economic credit," and its use is expected to remain within this credit limit, thereby ensuring sustainability. Nevertheless, a structured economic analysis is needed in future research to validate this assumption and support potential large-scale adoption.

Results

Food waste quantification in the GDO

The results of the bibliographic research are shown in Table 3.

Identifying a clear correlation between the waste data reported in the reviewed articles is problematic due to the lack of standardized data on food waste quantification across large-scale retail stores, particularly in the case of Italian supermarkets. Each store appears to use its own internal method for recording food waste, resulting in significant inconsistencies between locations and making it difficult to compare results meaningfully. In Cicatiello *et al*. (2016) the recordings were carried out only by a charity that works in collaboration with the store analyzed, therefore the data reported in the case study convert only the fraction of waste that is still edible and that could have been redistributed. No data were presented on the total amount of food waste generated by the store. On the other hand, Cicatiello *et al*. (2017) incorporated both internal store records and charity data, considering both edible and inedible waste. While Cicatiello *et al*. (2020) analyzed 13 supermarkets and did not present data on the average weight of the waste mass, but it shows an average value in terms of how many kg of total waste is produced per square meter of the store, with the stores area ranging from 650 m^2 and 2500 m^2.

A striking example of the variability in data recording methods can be seen in Cicatiello *et al*. (2017), where the store's internal records reported only 3 tons of edible waste, while a secondary recording, conducted by a charity, documented an additional 21.6 tons of edible waste, leading to a total of 24.6 tons of edible waste. This discrepancy underscores the significant challenges in food waste quantification and highlights the inefficiency of current recording systems. Such inconsistencies not only make it difficult to compare studies but also limit the representativeness of the data for the entire Italian supermarket sector.

As a result, estimating a national average of food waste in Italian supermarkets based on the available data is not feasible. The only comparison that can be made is in relation to the edible waste fraction, which appears relatively consistent between Cicatiello *et al*. (2016) and Cicatiello *et al*. (2017), 23.5 t and 24.6 t, respectively. This suggests that more standardized methodologies are needed to ensure consistent and comparable food waste data across different supermarkets and studies. Without this standardization, the ability to make reliable conclusions or formulate robust strategies for food waste reduction remains compromised.

However, starting from the case study data, it was possible to make comparisons in terms of which food category generates more waste (Table 4).

According to the literature, the most wasted products in supermarkets are fruit and vegetables, followed by baked goods, and the case studies presented in this work confirm this trend.

For instance, fruit and vegetables account for the largest share of food waste in both Cicatiello *et al*. (2017) and Cicatiello *et al*. (2020), with very similar percentages of 34% and 36%, respectively. However, in Cicatiello *et al*. (2016), this category represents only 8.4% of the total waste (about 2 tons), a notably lower figure. This discrepancy can be explained by the nature of the data: in Cicatiello *et al*. (2016), waste is recorded exclusively by a collaborating charity, and thus only includes products still suitable for human consumption. Therefore, the real total waste — including inedible or perished items — may be significantly higher. Supporting this hypothesis, Cicatiello *et al*. (2017) reports about 24 tons of wasted fruit and vegetables, of which only 0.5% were actually redistributed, due to their perishable nature and strict safety controls by charities.

When it comes to bakery products, the data show significant variability across studies. In Cicatiello *et al*. (2016), bakery items represent 70% of the total waste (17.3 tons), whereas in Cicatiello *et al*. (2017), they account for 31%, and only 18% in Cicatiello *et al*. (2020). Several factors contribute to this wide range:

- Supplier take-back agreements: In some supermarkets, bakery products (as well as dairy) may be returned to suppliers instead of being recorded as waste, thereby reducing their weight in the store's internal waste statistics (Cicatiello *et al*., 2020).
- In-store baking: Bread baked in-store is often not counted as finished product waste but rather as loss of raw ingredients, due to specific accounting practices. In Cicatiello *et al*. (2017), for example, only 1% of bakery waste was recorded by the store, while the actual figure — including the charity data — was much higher.
- High redistribution rates: Bakery products often maintain their edibility even after their shelf life, which makes them easier to redistribute. In Cicatiello *et al*. (2017), the redistribution rate for bakery items reached 99.6%, which explains the high percentages in studies based on charity-collected waste, such as Cicatiello *et al*. (2016).

As for meat products, the percentages of total waste are relatively consistent across studies: 8.3% (Cicatiello *et al*., 2016), 4% (Cicatiello *et al*., 2017), and 5% (Cicatiello *et al*., 2020). The slightly higher percentage in the first case study again reflects the fact that only edible waste was recorded. Since meat is often removed from shelves before expiration and still suitable for consumption, it is more likely to be redistributed and thus captured in charity data.

In the case of dairy products, the results are again inconsistent. Cicatiello *et al*. (2020) does not report on this category, while Cicatiello *et al*. (2016) finds less than 1% of total waste, and Cicatiello *et al*. (2017) reports 9%. Here too, the supplier take-back policy plays a major role: in some stores, unsold dairy products are returned to the supplier and excluded from internal waste statistics. Furthermore, dairy products, unlike bakery items, have extremely low redistribution rates — nearly zero according to Cicatiello *et al*. (2017) — due to their perishability and safety concerns. As a result, studies relying on data from redistributed waste (like Cicatiello *et al*., 2016) will underreport dairy waste, while studies using store inventory records (like Cicatiello *et al*., 2017) will show a higher impact.

Overall, the results of the case studies are consistent with the trends reported in the literature, confirming that fruit, vegetable and bakery products are the categories that most influence the total food waste. However ,the data should be evaluated carefully, since the variability in reported percentages across case studies is notable.

This variability is primarily due to differences in data sources (e.g., charity *v*. store records), store policies (e.g., take-back agreements with suppliers), accounting systems (e.g., how in-store production waste is recorded) and redistribution practices and rates.

Therefore, it is essential to interpret waste data within the context of each store's practices, and to advocate for more standardized recording methods that capture the full extent of waste across all categories. Only then can meaningful comparisons be made and reliable strategies for waste reduction developed.

Food waste quantification in the food service

In this bibliographic research, different sectors of the food service have been considered. For instance, a case study (Bux *et al*., 2023) regarding hospital's cafeteria, was considered. In this article two different methods of preparing a meal were confronted: "the cook-hold" and "cook-chill" catering. They have the same ingredients supplying, storage, preparation and cooking, but different steps follow cooking: the cook-chill, after the cooking phase, first refrigerate the meals, storage them in cold rooms at +3°C and then reheat them to 120°C for 50 min, while the cook-hold transport the meals at +65°C and serve them at the same temperature, no refrigeration involved. It has resulted that the cook-hold catering produces less waste (Table 5).

Another cafeteria considered is the school one. In fact, three case studies have been analyzed on this topic (Table 6).

The variability observed in the unserved food waste percentages among school catering studies is largely influenced by differences in the recording methods used. For instance, Pancino *et al*. (2021) and García-Herrero *et al*. (2024) report similar total waste values, whereas Boschini *et al*. (2018) shows a notably higher percentage. This discrepancy arises because García-Herrero *et al*. (2024) excludes categories such as fruit and bread from their calculations, while Boschini *et al*. (2018) includes them, where these categories account for over 45% of the total waste. When fruit and bread are excluded from Boschini *et al*.'s data as well, the percentage of unserved food waste drops to 7.6%, aligning more closely with García-Herrero *et al*. (2024). This clearly demonstrates that differences in what categories are included or excluded in waste quantification can significantly affect reported results. Therefore, when consistent recording methods are applied across studies, the data on unserved food waste in school canteens become much more comparable and reliable. This highlights the critical need for standardized waste measurement protocols to ensure accurate and meaningful comparisons across studies in the food service sector.

The last sector considered is represented by restaurants and, on this purpose, the case study by Principato *et al*. (2018) was analyzed. It emerged that waste is produced both in the kitchen and on the plate, which is caused by the consumer, and this one is generally higher (Table 7).

Valorization of food waste: waste hierarchy

As already mentioned in the introduction, the best condition is to not have any waste. Which means work in terms of prevention. One possibility, for supermarkets, could be to lower the temperature of the displays of some products, such as meat. This was the strategy proposed by Eriksson *et al*. (2016). They found that lowering temperatures from 8°C to 2°C could increase shelf life by up to 95% for certain foods and reduce waste significantly, particularly in the meat department. However, the environmental and economic costs—mainly due to higher electricity consumption—must be balanced. In fact, while the dairy sector showed the highest waste reduction potential, the environmental cost of energy use made this option less favorable compared to applications in the meat section, unless green energy is used.

Another strategy that supermarkets could use is discounting products close to the expiration date to encourage consumers to buy them. On the other hand, the food service sector has to find different solutions, for instance by implementing the use of doggy bags or reformulating the portions served.

When prevention fails, a waste is generated. For this reason, it is necessary to find a solution aimed to valorize food waste in raw materials or ingredients for new processes (Figure 2).

In the articles selected with the third bibliographic research many options are proposed. Some articles propose energy recovery to valorize food biomass, for example with incineration with energy recovery. This is the case of Schmidt *et al*. (2020), who evaluated different treatments for spent coffee grounds, including biodiesel production, anaerobic digestion (AD), composting, incineration, and landfill. Incineration was found to have the most favorable environmental performance in 14 of 16 categories. Similarly, Narisetty *et al*. (2022) examined bioethanol production from bread waste and showed a significant reduction in fossil energy use and photochemical oxidation compared to fossil-derived ethanol, although human toxicity and acidification increased by 30%. These solutions are better than simple landfill disposal, but there are more sustainable options.

One could be nutrient recovery, a topic covered in many articles. This is a very interesting category since it offers many opportunities. In fact, components can be extracted from the food matrix to be used to produce fortified foods, as demonstrated by Rațu *et al*. (2024), who showed that pumpkin peel powder (PPP), rich in carotenoids, polyphenols and fiber, can be used as a yogurt additive to enhance its nutritional and antioxidant properties. Their study showed that adding 2% PPP significantly improved the yogurt's nutritional value while also maintaining consumer acceptance in terms of texture and flavor. But the components extracted could also be used in the pharmaceutical or cosmetic industries. For instance, Zilia *et al*. (2023) investigated the recovery of collagen from sea urchin waste, a sustainable alternative to traditional bovine sources. Sea urchin collagen is not only safer and more readily available, but it also presents comparable functionality for use in skin care and cosmetic formulations. Furthermore, the pigments and antioxidants naturally present in sea urchin waste show potential for application in pharmaceutical and biomedical sectors, underlining the versatility of nutrient recovery in high-value industries. Moreover, nutrient recovery also includes processes such as anaerobic digestion and compost production, both extensively evaluated through Life Cycle Assessment (LCA) studies. Santagata *et al*. (2021) compared anaerobic digestion (AD), industrial composting (IC), and incineration. While AD showed the highest overall global impact, it performed better in specific categories such as global warming potential, particulate matter formation, and soil acidification, thanks to the energy recovery and use of digestate in agriculture. On the other hand, IC had the lowest total environmental impact, despite scoring worse in some impact categories, and required less energy support than incineration. The authors conclude that while incineration recovers energy, it poses more environmental risks due to ash production, whereas AD and composting provide more balanced and sustainable options for nutrient recovery.

In a separate study, Aleisa *et al*. (2024) found composting to be the most beneficial strategy overall, with the lowest environmental impact in nearly all categories, particularly in terms of climate change mitigation and mineral resource savings. They highlight that composting each ton of food waste can save about 50 kg of virgin nitrogen fertilizer. However, other strategies also offer advantages: for example, animal feed production performed best in categories like metal toxicity and land use efficiency, saving up to 0.33 m^2 of agricultural land per year. Meanwhile, anaerobic digestion stood out for fuel savings, generating about 20 kg of liquid fuel and over 200 kWh of electricity per ton of food waste. Incineration with energy recovery showed high impacts, especially in carbon footprint, but contributed to water footprint savings by replacing fossil energy.

Going further along the pyramid, another category is material recycling, where the focus is on transforming waste material into a new, valuable product. One relevant example is the production of bioplastics from food waste, such as polyhydroxyalkanoates (PHA), a family of biodegradable polymers obtained via microbial fermentation. Nitkiewicz *et al*. (2020) compared different production scenarios using various raw materials: crude vegetable oil, glycerol (a by-product of biodiesel), and used vegetable oil, the latter being the most environmentally sustainable option. The use of waste-derived feedstocks significantly reduced environmental impacts compared to virgin resources, particularly in terms of global warming potential and resource depletion. This study highlights how the environmental performance of bioplastics is highly dependent on the choice of feedstock and the efficiency of the microbial production process.

Another innovative material recycling strategy is the production of bio-surfactants, such as sophorolipids (SLs), using bakery waste oil (BWO) as a hydrophobic substrate. Surfactants are widely used in industrial and household applications, and bio-based alternatives are gaining attention due to their biodegradability and lower toxicity. Miao *et al*. (2024) demonstrated that using BWO instead of conventional substrates like oleic acid results in lower environmental impacts, especially for global warming potential and cumulative energy demand. The study also compared BWO with other food waste-derived substrates and found that BWO offered the best environmental performance, making it a promising circular strategy for transforming food waste into high-value, eco-friendly products. The two following waste management methods are both related to the reuse of food waste, which can be reused for animal consumption, by converting suitable food waste, especially dry fractions like bread, into animal feed (Vandermeerscha *et al*., 2014), or for human consumption, through donation, which allows the redistribution of excess edible food instead of discarding it (Damiani *et al*., 2021).

Vandermeersch *et al*. (2014) compared two scenarios: one where all food waste was treated via anaerobic digestion, and another where bread waste was processed into animal feed while the rest was digested anaerobically. The second scenario proved more advantageous in several environmental categories, particularly in land use, metal depletion, and terrestrial acidification, due to the avoidance of primary feed production and reduced agricultural inputs. However, the feed production process (drying, shredding) can contribute to environmental impacts, and therefore, this strategy is especially beneficial when applied selectively to high-dry-matter waste fractions.

Damiani *et al*. (2021), in an Italian case study, found that food donation had lower environmental impacts than composting, anaerobic digestion, or incineration across almost all evaluated categories. Similarly, Eriksson *et al*. (2015) analyzed six waste management scenarios -landfill, incineration, composting, anaerobic digestion, animal feed, and donation- for five different food types (Table 8). Greenhouse gas emissions associated with each waste management option and each food type (Eriksson *et al*., 2015).

They found that donation resulted in low greenhouse gas emissions, especially for high-impact foods like meat, although, for some products (e.g. bananas, lettuce), anaerobic digestion performed slightly better. However, these data only concern environmental impacts, without considering the social aspect. If the latter was considered, donation would be the most efficient solution. Since sustainability is not only environmental, but also important to pay attention to social sustainability as well. The case study below was conceived, in this regard, not only from an environmental perspective, but also considering the social impact of the service proposed.

Case study

Environmental impact

The environmental sustainability of the food hub was assessed through a comprehensive life cycle assessment, considering both environmental credits and debts. Credits are associated with the phases "Product at retail", which consists in the environmental impacts of production and distribution avoided through recovery, and "Avoided waste", which is the environmental impact that would have occurred if those foods had been disposed of and not recovered.

Conversely, environmental debts are attributed to the operational phases (Figure 3), including:

- Collection, where the main impact factor is the mileage traveled by the refrigerated van,
- Quality screening, where the impact factors are the disposal of the non-edible fraction and its packaging and their transportation to the disposal place,
- Storage, where the electricity needed to power the cold storage rooms that has the greatest impact,
- Redistribution, where, as for the collection phases, the impact is due to the donated food transportation, in this case to the NGO front-line.

Starting from the data presented in materials and methods, with SimaPro it was possible to calculate the environmental impact of these single steps and, by summing them together, of the new service considered in its entirety.

From this graphic it emerges that the phases that overall generate the highest impact are storage and redistribution. The collection phase has a considerable impact in the human toxicity (cancer), while the quality screening phase was found to be the most impactful only for the categories of ecotoxicity and terrestrial eutrophication.

The environmental impact balance of the new service assesses both the environmental credits (derived from avoided impacts) and the environmental debts (generated by the recovery, quality screening, storage and redistribution activities), therefore, by adding to Figure 3 the carbon credits obtained from the recovery of food surpluses, the graph in Figure 4 is obtained.

This graph shows that the environmental net balance of the food hub activity is negative (<0) because the credits, related to "retail product" and "waste avoided", significantly exceed the carbon debts due to transportation, storage and waste management. Even the impact categories with slightly higher values than the others in terms of debts, such as the use of mineral, metal and fossil resources, photochemical ozone formation, human toxicity (cancer) freshwater eutrophication and climate change, are negligible, since they affect the total balance for less than 1%. These results underscore the significant environmental benefits of the hub, they demonstrate that donation is a better option when compared to disposal.

Social impact

Social sustainability is often overlooked compared to environmental sustainability, but in reality, it is a very important issue. In fact, Goal 2 of the United Nations 2030 Agenda for Sustainable Development (United Nations, 2015) concerns the end of world hunger and the achievement of food security.

To assess the importance of this new proposed service, it was calculated how many portions of food could be obtained from the donated food. Banco Alimentare stated that a meal corresponds to 500 g of food. Therefore, by doubling the kg of food recovered by the NGOs on the front line (about 73.5 tons), it is possible to estimate the number of meals produced, which amounts to 146,986.

Considering that people must eat every day, dividing the total meals by 365, it was possible to calculate that 402 meals can be provided every day. Assuming that three meals are served daily to those in need (breakfast, lunch, and dinner), it was possible to estimate that the service helps 134 people every day, a figure that confirms the social effectiveness of this initiative. These data confirm that donation is the best solution within the waste hierarchy, not only for its positive impact on the environment, but also for its social sustainability. In a context where hunger and malnutrition are global problems, food recovery and distribution not only reduce waste, but also contribute to improving the lives of many vulnerable people.

Furthermore, a small nutritional focus was also made, because it is important not only the quantitative aspect of the food donated to the needy, but also the qualitative one.

Knowing the nature of the donated products and their quantities, it was possible, thanks to the data retrieved from CREA (Centro di Ricerca Alimenti e Nutrizione (CREA), 2023; *Linee guida per una sana alimentazione*, 2018), and USDA (U.S. Department of Agriculture, Agricultural Research Service, 2013), to create estimates of the nutritional composition of the donated food (Figure 5).

Figure 5 shows that carbohydrates (68%) represent most of the calories in donated food. According to LARN (Società Italiana di Nutrizione Umana-SINU, 2014), this is the macronutrient that should be consumed in greater quantities, but the proposed value is lower, between 45% and 60%. Proteins contribute, in terms of calories, to 17% of the total, a value included in the range determined by the LARN (10-20%) (Società Italiana di Nutrizione Umana-SINU, 2014). While the calories derived from lipids (15%) are lower than what is expected by LARN (25-35%) (Società Italiana di Nutrizione Umana-SINU, 2014).

Although the analysis focused on macronutrients, it is important to also consider micronutrients. Fruits and vegetables, which constitute the majority of donated food (67%), are a rich source of essential vitamins and minerals, which can represent a significant health benefit for the people benefiting from the service.

Conclusions and future perspectives

In conclusion, it can be said that the current registration methods in the large-scale retail trade are not efficient enough. In the future, it would be necessary to create universal and standardized waste recording and monitoring systems. These systems would enable consistent data collection across different stores, facilitate comparison, and support the estimation of average waste values at the sector level. This, in turn, would allow more effective benchmarking, policy-making, and targeted waste reduction strategies. It has also emerged that the share of waste due to the consumer is significant. Therefore, a solution to reduce it could be to educate and raise awareness among consumers, especially children, for example with long-term projects in schools, to have more aware consumers in the future (Piras *et al.*, 2023). These could include interactive workshops on food value and waste reduction, school garden projects to reconnect students with the food production cycle, gamified challenges to encourage sustainable behaviors, and partnerships with local food recovery organizations. Educating younger generations can lead to lasting cultural change and more responsible consumption patterns over time.

The case study has proven to be optimal both in environmental and social terms. In fact, it has a negative net environmental impact, but it could be even lower by intervening in the factors that cause it: transportation, electricity used for conservation and waste management.

As for electricity, one possibility might be using low consumption cold storage rooms. While, to reduce the environmental impact due to transportation, the redistribution phase can be optimized by assuming to use a refrigerated van that collects the donated food from the hub, passes through the individual NGOs and then comes back, following the shortest route. Since all NGOs receive donated food with different frequencies, six different routes have been designed that are repeated cyclically, based on the cases that arise. The total kilometers that the van would travel in a year in this case (7,478.9 km) are 3,048.7 km less than those traveled with the current solution (10,527.6 km). With SimaPro the impact of the current solution with the new solution, in which the kms are reduced and a single refrigerated van is used, were compared. Four different types of vans were considered: freezing, cooling euro 5, cooling euro 6 and a cooling van with a larger capacity (3.5-7.5 t). Each of these cases presented a lower environmental impact than the solution currently in use. Therefore, the solution proposed here is more sustainable and would reduce the environmental impacts related to the distribution phase.

Another aspect that emerged in the case study is that, currently, the food donated in the case study did not correspond to the average nutritional needs of a human being. In fact, while the percentage of proteins was consistent with the levels established by the LARN, the intake of carbohydrates was higher, while that of lipids was lower. To improve this aspect, taking advantage of the presence of different hubs in the territory, a network based on macronutrients could be created, making the donated food compliant with the reference values of the LARN. All this with the aim of giving the needy a nutritionally balanced meal.

Future research should focus on assessing the economic sustainability of the proposed service, with particular attention to its scalability and integration into existing systems. Although the current model is based on voluntary donations and is conceptually designed to operate within an "economic credit" framework, a more rigorous cost-benefit analysis is necessary to confirm its feasibility in real-world settings. Additionally, exploring potential incentives, reimbursement mechanisms, or public-private partnerships could support broader adoption. Finally, longitudinal studies could help measure both the economic and social impacts over time, providing a more comprehensive evaluation of the service's value.

References.

Aleisa, E., Alsaleh, A., 2024. Upcycling food waste into animal feed: An environmental assessment based on food waste quantities in different district types in Kuwait. J. Eng. Res-Kuwait. (In press).

Arias, A., Feijoo, G., Moreira, M.T., 2022. Assessing of the most appropriate biotechnological strategy on the recovery of antioxidants from beet wastes by applying the life cycle assessment (LCA) methodology. Food Bioprod. Process. 135:178-189.

Boschini, M., Falasconi, L., Giordano, C., Alboni, F., 2018. Food waste in school canteens: A reference methodology for large-scale studies. J. Clean. Prod. 182:1024-1032.

Bux, C., Zizzo, G., Amicarelli, V., 2023. A combined evaluation of energy efficiency, customer satisfaction and food waste in the healthcare sector by comparing cook-hold and cook-chill catering. J. Clean. Prod. 429:139594.

Cappelli, A., Parretti, C., Cini, E., Citti, P., 2019. Development of a new washing machine in olive oil extraction plant: A first application of usability-based approach. J. Agric. Eng. 50:949.

Casson A., Ferrazzi G., Guidetti R., Bellettini C., Narote A.D., Rollini M., et al., 2024. Wholesale fruit and vegetable market in Milan: Turning food surpluses into environmental gains. J. Clean. Prod. 462:142625.

Centro di Ricerca Alimenti e Nutrizione, 2023. [Banca dati di composizione degli alimenti per studi epidemiologici in Italia (BDA)].[in Italian]. Rome, Centro di Ricerca Alimenti e Nutrizione. Available from: https://bda.crea.gov.it/

Centro di Ricerca Alimenti e Nutrizione (CREA), 2018. [Linee Guida per una Sana Alimentazione].[in Italian]. Rome, Centro di Ricerca Alimenti e Nutrizione. Available from: https://www.crea.gov.it/web/alimenti-e-nutrizione/-/linee-guida-per-una-sana-alimentazione-2018

Cicatiello, C., Franco, S., 2020. Disclosure and assessment of unrecorded food waste at retail stores. J. Retail. Consum. Serv. 52:101932.

Cicatiello, C., Franco, S., Pancino, B., Blasi, E., 2016. The value of food waste: An exploratory study on retailing. J. Retail. Consum. Serv. 30:96-104.

Cicatiello, C., Franco, S., Pancino, B., Blasi, E., Falasconi, L., 2017. The dark side of retail food waste: Evidences from in-store data. Resour. Conserv. Recy. 125:273-281.

CONAI, 2024. [Riciclo imballaggi: nel 2023 percentuale in crescita].[in Italian]. available from: https://www.conai.org

Damiani, M., Pastorello, T., Carlesso, A., Tesser, S., Semenzin, E., 2021 Quantifying environmental implications of surplus food redistribution to reduce food waste. J. Clean. Prod. 289:125813.

Eriksson, M., Spångberg, J., 2017. Carbon footprint and energy use of food waste management options for fresh fruit and vegetables from supermarket. Waste Manag. 60:786-799.

Eriksson, M., Strid, I., Hansson, P., 2015. Carbon footprint of food waste management options the waste hierarchy e a Swedish case study. J. Clean. Prod. 93:115-125.

Eriksson, M., Strid, I., Hansson, P., 2016. Food waste reduction in supermarkets – Net costs and benefits of reduced storage temperature. Resour. Conserv. Recy. 107:73-81.

European Commission, 2008. Directive (2008/98/EC) of the European parliament and of the council of 19 November 2008 on waste and repealing certain Directives. Available from: https://eur-lex.europa.eu/eli/dir/2008/98/oj/eng

European Commission, 2020. Circular Economy Action Plan – For a cleaner and more competitive Europe. Available from: https://op.europa.eu/en/publication-detail/-/publication/9dc6aa01-39d2-11eb-b27b-01aa75ed71a1

FAO, 2011. Global food losses and food waste. Available from: https://www.fao.org/4/mb060e/mb060e00.htm

FAO, 2014. Food wastage footprint: fool cost-accounting. Available from: https://openknowledge.fao.org/server/api/core/bitstreams/6a266c4f-8493-471c-ab49-30f2e51eec8c/content

FAO, 2015. Food wastage footprint & climate change. Available from: https://openknowledge.fao.org/server/api/core/bitstreams/7fffcaf9-91b2-4b7b-bceb-3712c8cb34e6/content

García-Herrero, L., De Menna, F., Vittuari, M., 2019 Food waste at school. The environmental and cost impact of a canteen meal. Waste Manag. 100:249-258.

Miao, Y., Hu, X., To, M.H., Wang, H., Qin, Z., Mou, J., et al., 2024. Environmental evaluation of emerging bakery waste oil-derived sophorolipids production by performing a dynamic life cycle assessment. Sustain. Prod. Consump. 47:59-70.

Narisetty, V., Nagarajan, S., Gadkari, S., Ranade, V.V., Zhang, J., Patchigolla, K., et al., 2022. Process optimization for recycling of bread waste into bioethanol and biomethane: A circular economy approach. Energy Convers. Manag. 266:115784.

Nitkiewicz T., Wojnarowska M., Sołtysik M., Kaczmarski A., Witko T., Ingrao C., Guzik M., 2020. How sustainable are biopolymers? Findings from a life cycle assessment of polyhydroxyalkanoate production from rapeseed-oil derivatives. Sci. Total Environ. 749:141279.

Pancino, B., Cicatiello, C., Falasconi, L., Boschini, M., 2021. School canteens and the food waste challenge: Which public initiatives can help? Waste Manag. Res. 39:1090-1100.

Piras, S., Righi, S., Banchelli, F., Giordano, C., Setti, M., 2023. Food waste between environmental education, peers, and family influence. Insights from primary school students in Northern Italy. J. Clean. Prod. 383:135461.

Principato, L., Pratesi, C.A., Secondi, L., 2018. Towards zero waste: an exploratory study on restaurant managers. Int. J. Hosp. Manag. 74:130-137.

Rațu, R.N.G., Carlescu, P.M., Veleșcu, I.D., Arsenoaia, V.N., Stoica, F., Stanciuc, N., et al., 2024. The development of value-added yogurt based on pumpkin peel powder as a bioactive powder. J. Agr. Food Res. 16:101098.

Santagata, R., Ripa, M., Genovese, A., Ulgiati, S., 2021. Food waste recovery pathways: Challenges and opportunities for an emerging bio-based circular economy. A systematic review and an assessment. J. Clean. Prod. 286:125490.

Scherhaufer, S., Moates, G., Hartikainen, H., Waldron, K., Obersteiner, G., 2018. Environmental impacts of food waste in Europe. Waste Manag. 77:98-113.

Schmidt Rivera, X.C., Gallego-Schmid, A., Najdanovic-Visak, V., Azapagic, A., 2020. Life cycle environmental sustainability of valorization routes for spent coffee grounds: From waste to resources. Resour. Conserv. Recy. 157:104751.

Società Italiana di Nutrizione Umana (SINU), 2014. [LARN – Livelli di Assunzione di Riferimento di Nutrienti ed energia per la popolazione italiana].[in Italian]. Rome, SICS. Available from: https://sinu.it/tabelle-larn-2014/

Teigiserova, D.A., Hamelin, L., Thomsen, M., (2020). Towards transparent valorization of food surplus, waste and loss: Clarifying definitions, food waste hierarchy, and role in the circular economy. Sci. Total Environ. 706:136033.

U.S. Department of Agriculture, Agricultural Research Service, 2023. FoodData Central. Available from: https://fdc.nal.usda.gov/

Vandermeerscha, T., Alvarenga, R.A.F., Ragaert, P., Dewulf, J., 2014. Environmental sustainability assessment of food waste valorization options. Resour. Conserv. Recy. 87:57-64.

Zilia, F., Orsi, L., Costantini, M., Tedesco, D.E.A., Sugni, M., 2023. Case study of Life Cycle Assessment and sustainable business model for sea urchin waste. Clean. Environ. Syst. 8:100108.

Table 1. Operational phases of the new service analyzed.

	Input	Value	Unit	Output	Value	Unit
Collection	Donated food	74235.5	kg	Donated food	74235.5	kg
	collection	10608	km			
Storage	Donated food	7435.5	kg	Donated food (99%)	73493.1	kg
	Meat cold storage unit (0-5°C)	6912	kWh	Waste (1%)	742.4	kg
	Fruit cold storage unit (0-10°C)	6240	kWh			
Redistribution	Donated food	73493.1	kg	Donated food	73493.1	kg
	Redistribution	10527.6	km			

Table 2. Environmental impact categories considered in the study (assessment method: Environmental Footprint (EF) .

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

Table 3. Results confrontation between the articles considered.

Articles	Store area (m^2)	Edible waste (t)	Total waste (t)	Kg/m^2 edible waste	Kg/m^2 total waste
Cicatiello *et al.*, 2016	5300	23.5	-	4.5	-
Cicatiello *et al.*, 2017 (internal registration)	>4500 55% food departments	3	49	-	-
Cicatiello *et al.*, 2017 (total)	>4500 55% food departments	24.6	70.6	-	-
Cicatiello *et al.*, 2020	Range: 650-2500	-	-	-	19-average

Table 4. Percentage values of waste divided by food category.

Articles	Fruit and vegetables	Bakery products	Meat	Dairy
Cicatiello *et al.*, 2016	8.4%	70%	8.30%	1%
Cicatiello *et al.*, 2017	34%	31%	4%	9%
Cicatiello *et al.*, 2020	36%	18%	5%	-

Table 5. Waste results from the hospital cafeteria case study.

Preparation method	Waste %	Waste/meal (weekly)	Annual waste
Cook-chill	13.79%	0.99 kg	29.71 t
Cook-hold	2.12%	0.21 kg	4.56 t

Table 6. Waste results from the school cafeterias case studies.

Articles	**Total waste (no kitchen waste)**	**g of waste/person**	**Plate waste**	**Non-served waste (NSW)**	**NSW excluding bread and fruit**
Garcià-Herrero *et al.*, 2024	20-29%	136	15-25%	5%	5%
Boschini *et al.*, 2018	41%	213.8	22%	19%	7,6%
Pancino *et al.*, 2021	28.60%	160.7	-	-	-

Table 7. Waste results from the restaurants' case study.

Waste	**Value**
Kitchen food waste	12.93%
Client food waste	15.83%

Table 8. Greenhouse gas emissions associated with each waste management option and each food type (Eriksson *et al.*, 2015).

Scenario/food product	**Banana (kg CO_2eq / kg food waste)**	**Chicken (kg CO_2eq / kg food waste)**	**Lettuce (kg CO_2eq / kg food waste)**	**Beef (kg CO_2eq / kg food waste)**	**Bread (kg CO_2eq / kg food waste)**
Landfill	1.4	3.1	0.21	2.1	1.9
Incineration	0.10	-0.31	0.25	0.003	-0.67
Composting	0.043	0.043	0.043	0.043	0.043
Anaerobic digestion	-0.38	-0.26	-0.047	-0.67	-0.55
Animal feed	-0.011	-0.038	0.005	-0.030	-0.13
Donation	-0.12	-0.35	-0.013	-0.31	-0.61

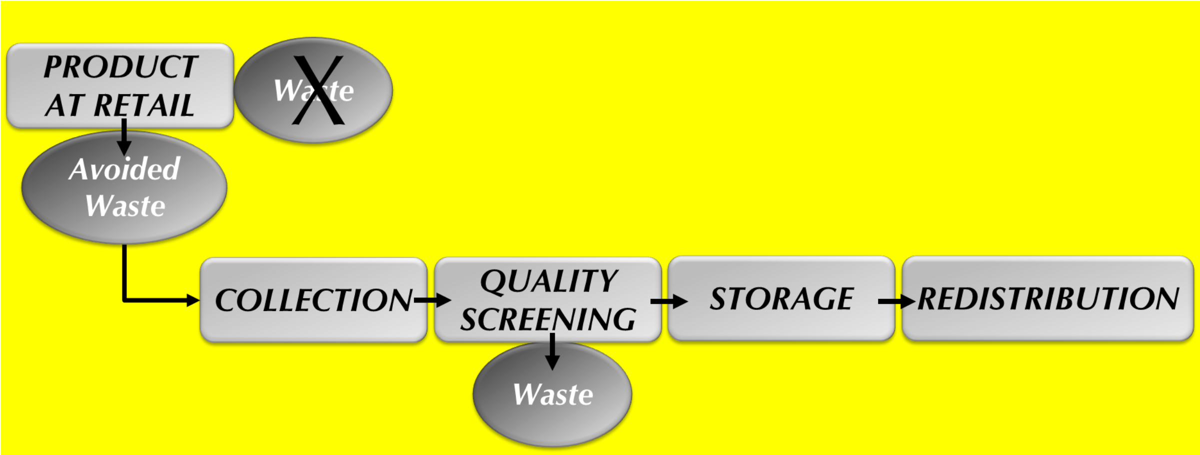

Figure 1. **Representation of phases in the 'cradle-to-gate' approach.** The figure describes the phases surplus food goes through from the initial stages of production until it is recovered and redistributed through food hubs. Based on Casson *et al*. J. Clean. Prod. 2024;462:142625.

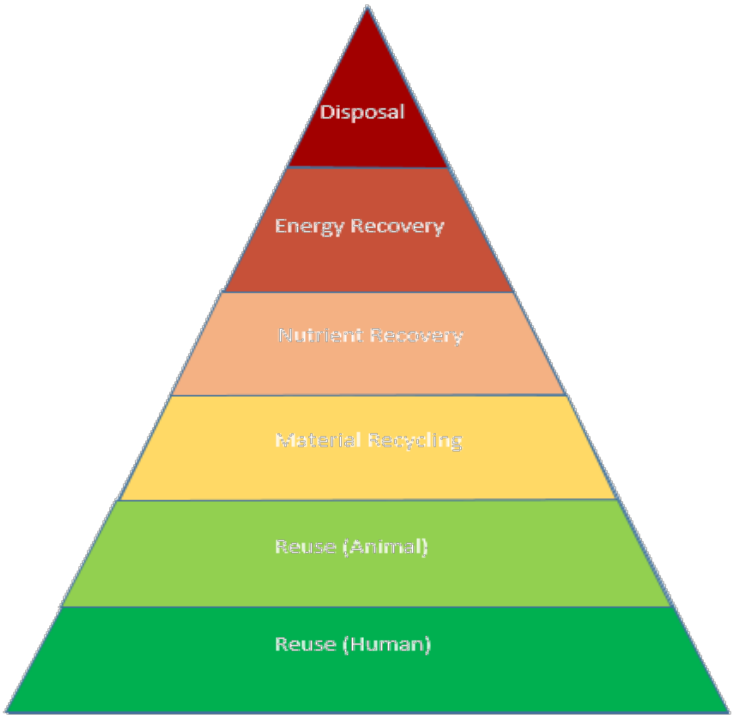

Figure 2. Waste hierarchy pyramid. From the worst option (in red) to the best option (in green).

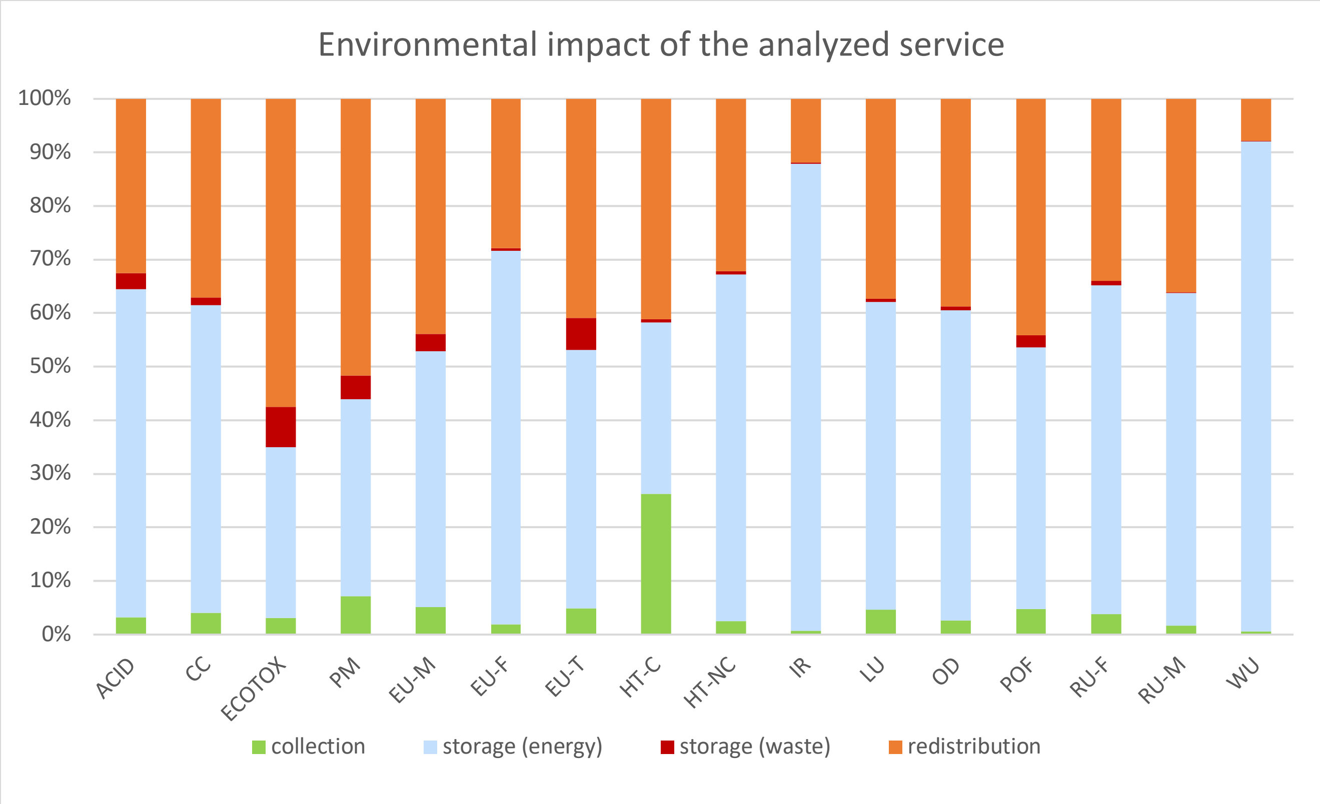

Figure 3. Environmental impact of the service analyzed.

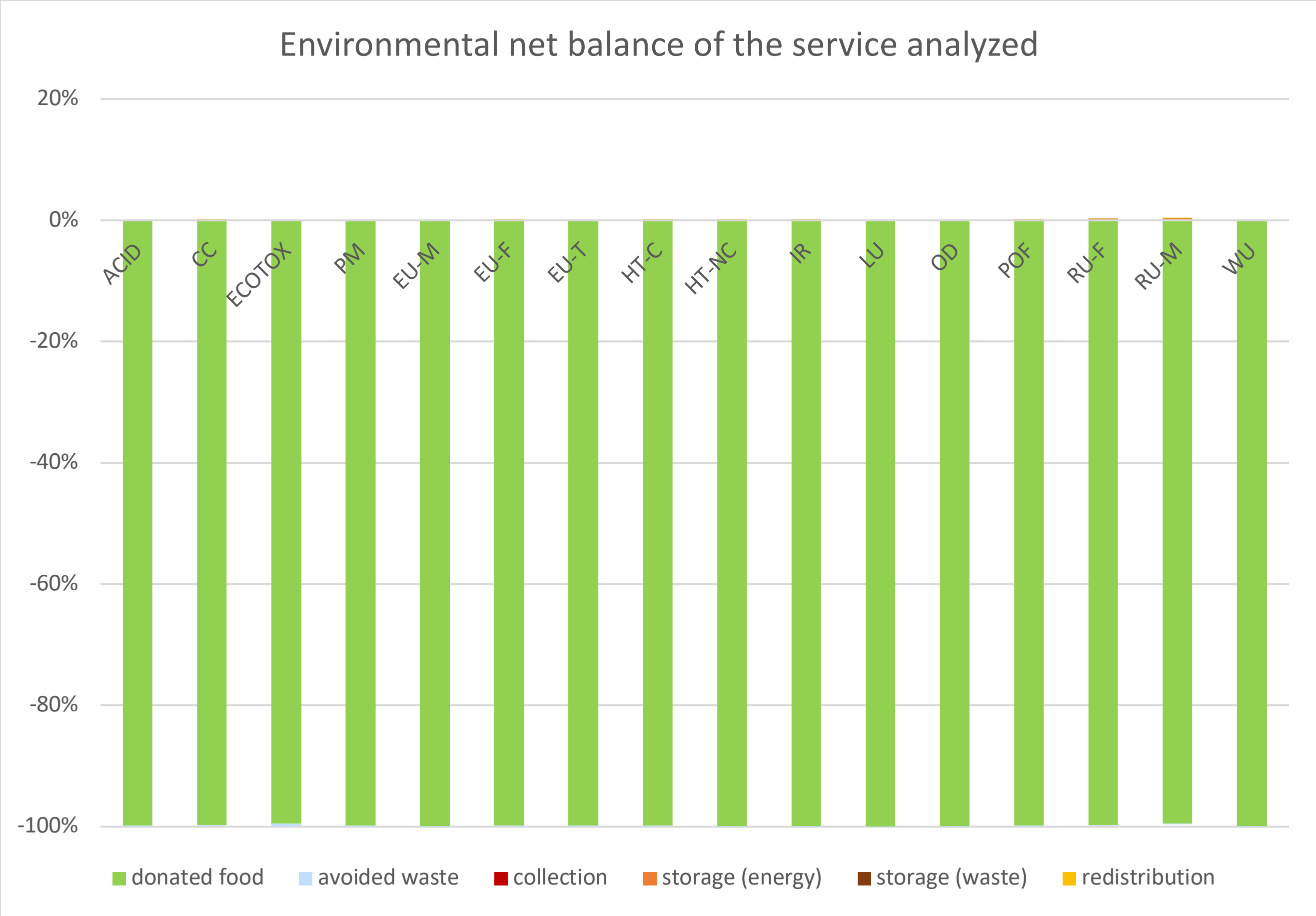

Figure 4. Environmental net balance of the service analyzed. Debts are represented by the part of the graph above 0 (red, orange, yellow and brown), credits by the part below zero (green, light blue).

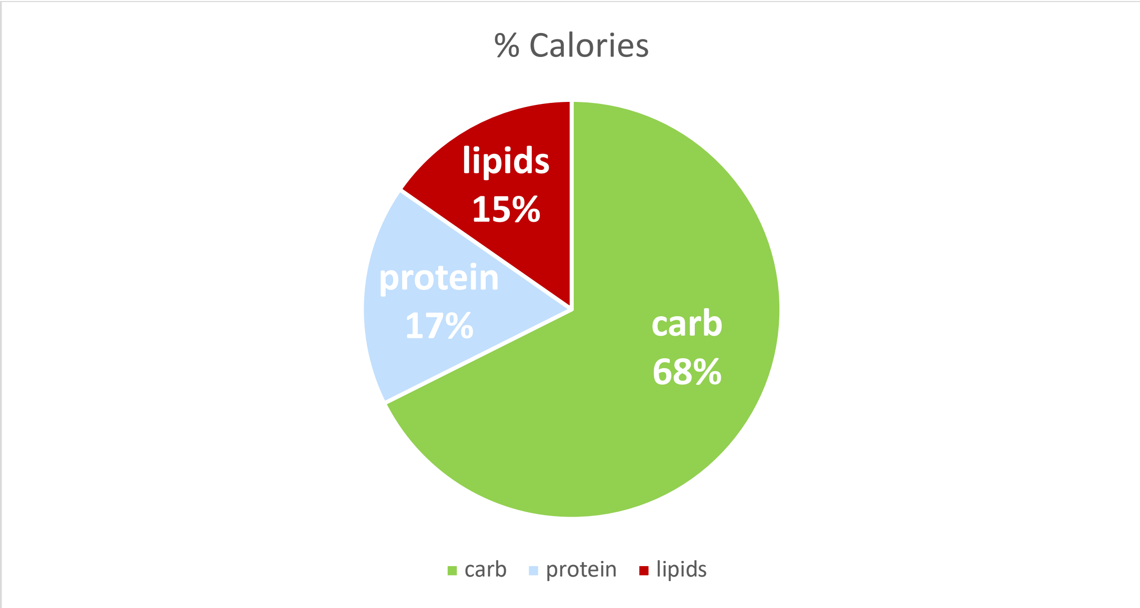

Figure 5. Calories distribution of the donated food.