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Quantifying environmental implications of surplus food redistribution to reduce food waste

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ABSTRACT

Ensuring access to food for the most vulnerable is one of the objectives of the UN 2030 Agenda for Sustainable Development. Rethinking food production and distribution systems in light of this need makes it imperative to limit the environmental burden of food supply chains to meet the increasing demand of a rapidly growing world population. One of the most important problems of food supply chains is food waste, which leads to a huge waste of resources for the production of foodstuffs that end up not fulfilling the function for which they were produced. A powerful strategy to address this problem is the recovery and redistribution of food that is still edible to socially and economically disadvantaged people. In this article Life Cycle Assessment (LCA) is applied to the study of environmental burdens and benefits of food redistribution following attributional and consequential LCA approaches. Data on surplus food recovered is collected from local charities and the impact of their activities is compared with that of the treatment of food waste by incineration, anaerobic digestion and composting. All midpoint impact categories of ReCiPe (hierarchist) are considered in life cycle impact assessment of 1 kg of food wasted or donated. The study highlights the great variability of recovered food locally, with respect to quantity and type. The life cycle of surplus animal-based food has the greatest impact (e.g. up to 70% kg CO_2 eq/kg in waste treatment scenario). Food donation reduces the average impact of the studied systems (e.g. 1.9 kg CO_2 eq/kg net environmental benefit). However, efficient mechanisms of recovery and redistribution are required, in terms of sizing, consumptions and logistics, to ensure a significant environmental improvement over food waste treatment.

1. Introduction

Since 2015, the global number of undernourished people halted its decline and gradually raised back to 2010 level of around 820 million, more than 10% of the world population. Today, one out of four people suffers from moderate to severe food insecurity, meaning that access to essential food quantity and quality cannot be constantly guaranteed throughout the year. This happens with different proportions all around the globe. More than half of the population is affected in Africa, 30% in South America, 23% in Asia and 8% in Europe and North America (FAO et al., 2019). Tackling food loss and waste has become even more important in responding to the challenge of providing food for a global population that is projected to reach 10 billion by 2050. Against this background, the Food and Agriculture Organization of the United Nations (FAO) estimated that the food lost or wasted in 2011 represented one third of the food produced but still much effort is being put into improving methods to quantify post-harvest loss and waste, especially in food retail and consumption phases (FAO, 2019).

The social, environmental and economic implications related to food waste have encouraged nations to draw up agreements to take on this issue. For instance, in the 2050 *Roadmap to a Resource Efficient Europe*, the European Commission (EC) committed to halve the disposal of edible food waste by 2020 (EC, 2011). In 2014 the 54 member countries of the African Union signed the Malabo Declaration, to try to halve post-harvest losses by 2025 (AUC, 2014). In the same year, the Community of Latin American and Caribbean

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States adopted the CELAC Plan for Food and Nutrition Security and the Eradication of Hunger (2025) (FAO et al., 2014), suggesting actions to reduce food loss and waste. More recently, reducing food loss and waste became an objective of the UN 2030 Agenda for Sustainable Development (United Nations, 2015) to achieve global food security (goal 2) and ensure sustainable production and consumption patterns (goal 12). Specifically, the signatories of Agenda (2030) have committed to halve per capita global food loss in supply chains and food waste in distribution and consumption by 2030. To support the achievement of Sustainable Development Goals (SDGs) related to food waste in Europe, the EC defined the actions to be undertaken by member states from 2016 onwards. With the *EU Action Plan for the Circular Economy* a stakeholder platform on food waste has been launched, and better and harmonized methods to account for food waste are being developed along with statutory instruments to facilitate food waste use for feed production and food donation of edible surpluses (EC, 2015). This initiative led to the approval by member states of the *EU Guidelines on Food Donation* to complement and support the implementation of national legislation on food surplus redistribution (EC, 2017).

Against this background, this article aims to provide support to the development of food waste management strategies, analyzing their potential environmental implications. In particular, we want to highlight the aspects to be taken into account in developing environmentally significant food waste recovery policies at the local scale through foodstuff donation. To meet this purpose, we first describe current definitions of food loss and waste. Secondly, the causes, the amount and the environmental implications of food loss and waste along the food production and consumption cycle are examined. Finally, a case study is presented where we quantify food recovered and donated by local charitable organizations to assess and discuss life cycle environmental burdens and benefits, thereby contributing to the existing limited literature on operational food redistribution systems at the territorial level.

2. Framing the issue of food waste

Despite the worldwide well-recognized importance of food waste from an environmental, social and economic viewpoint, there is not yet a common and shared definition on what food waste is and what it concerns. FAO and WRI (World Resources Institute) distinguish between food loss and food waste, taking into consideration the phase of the value chain in which it is generated: *food loss* refers to the food quantity or quality lost in the production, processing, storage and distribution stages. *Food waste* instead, usually occurs at retail and consumption stages and refers to food that is thrown away either before or after it spoils as well as to the alternative use (non-food) of food that is edible and safe for human consumption (FAO, 2019; Searchinger et al., 2019). In the EU-funded project FUSIONS (Östergren et al., 2014) and in Caldeira et al. (2019a) food waste is defined as the edible and inedible part of food discarded from the supply chain to be recovered or disposed (including crops ploughed in/not harvested, organic waste composted, treated by anaerobic digestion, co-generation, incineration, processed for bioenergy production, disposed to sewer, landfilled or discarded to sea). Beretta and Hellweg (2019) define food waste as food originally produced for human consumption and directed to non-food use (e.g. animal feed) or wasted. The EC refers to surplus food as finished or semi-finished food products, or ingredients at any stage of the food production and distribution chain that are suitable for human consumption but do not meet manufacturer or customer specifications, while Albizzati et al. (2019) refer to food waste as the share of surplus food sent to disposal. Since this work is focused specifically on food products for human consumption and on alternative management of surplus food, the latter two definitions are adopted.

2.1. Drivers and food waste quantification

As reported above, FAO estimated that the food lost or wasted in 2011 in global food supply chains represents the 32% of the food produced in weight. Using FAO Food Balance Sheets, Lipinski et al. (2013) made an estimate of food waste based on calories. The authors highlighted a clear difference between the two accounting methods for lost or wasted cereals (19% of the total food waste by weight, 53% by calories) and fruit and vegetables (44% by weight, 13% by calories), due to higher water content in fruit and vegetables. Parfitt et al. (2010) conducted a review of post-harvest losses, both for perishable and non-perishable food. They state that grain is lost for about 15% whilst one third of the production of fruits and vegetables is lost before it reaches consumers.

Food is wasted at different stages of the food supply chain in developing and developed countries: in the first ones harvesting and primary production are critical. Unpredictable factors can occur, such as weather damages, diseases and environmental pollution, along with premature or inefficient harvesting. During food processing and transformation, food waste is strongly connected to the lack of decent conservation and transportation systems, lack of transformation facilities or failures in manufacturing and budgetary limitations. Food waste from consumption is limited in developing countries whereas it is particularly relevant in industrialized countries, where demand of perishable products and food transformation levels are high. Retailers standards, customers preferences and market trends play also an important role in determining which products actually make it onto the supermarket shelf to be purchased and consumed (FAO, 2019; 2011; Lipinski et al., 2013).

Household food waste, on the other hand, can be distinguished in unavoidable and avoidable: the first refers to food wasted during preparation, such as peels, bones and shells; the avoidable share instead is the excess food cooked or prepared and not consumed or food exceeding the expiry date (Bernstad Saraiva Schott and Andersson, 2015). The amount of avoidable food waste is a consequence of consumer behavior and attitude but also family size and culture of origin. For instance, in 2010 UK total household food waste reported was 8.3 Mt per year, whereas in the United States families wasted 211 kg each per year of edible food (Parfitt et al., 2010), or between 56.7 and 72.6 Mt per year according to Gunders et al. (2017).

The huge contribution of household consumption to food waste is highlighted also by the FUSIONS project (Östergren et al., 2014): in 2012, in Europe household consumption accounted for 53% of the total food waste and together with the processing phase represented the 72%, including edible and inedible parts. Caldeira et al. (2019a) confirmed the European trend estimating that 46% of European food waste is generated in households, 25% in primary production, 24% in processing and manufacturing and 5% in distribution and retail, including edible and inedible food and not considering waste directed to animal feed.

2.2. Environmental impact of food production and waste

Agriculture and livestock farming carry the greatest portion of the overall environmental burden of food supply chains, deriving from energy consumption, emissions of greenhouse gases (GHG), nutrients, particulate matter and heavy metals emissions. In particular, more than 30% of the total GHG emissions of food supply chains are linked to agronomic activities and land use change (Ingram, 2011; Notarnicola et al., 2017). Agriculture is also known to be a major driver of biodiversity and pollinators decline due to intensive practices and use of agrochemicals, with significant and usually underestimated effects also at sub-lethal exposures (Dicks et al., 2016; Potts et al., 2010). A major share of GHG emissions is also represented by food processing, which is responsible for a non-negligible water consumption and depletion of natural resources for packaging as well. Moreover, transport and logistics of intermediate and final products represent another important environmental burden to be considered (Ingram, 2011; Notarnicola et al., 2017).

Depending on the food category, however, impacts can be very different. For instance, a hierarchy has been observed between different food types with regard to global warming potential (GWP). Beef produces an average emission of 28.7 kg CO_2 eq/kg whereas rice generates 2.7 kg CO_2 eq/kg. The efficiency of global supply chains is also different depending on where the production stage takes place, due to climatic reasons, but also techno-economic factors. For example, 1 L of milk produced in Europe has a GWP of 1.3 kg CO_2 eq, while the same quantity in Asia and Africa generates 2.5 and 3.3 kg CO_2 eq respectively (Clune et al., 2017). However, to fully understand what the environmental implications in different countries are, impacts have to be normalized considering local diets. For instance, in 2019 fresh dairy products consumption per capita in Asia, Africa, and Europe were quite different (26 kg in Africa, 56 kg in Asia, and 101 kg in Europe, according to OECD/FAO, 2020). Concerning potential biodiversity loss, a similar hierarchy has been observed. Animal products are deemed to account for around 70% of total species loss caused by food consumption in Europe. The most relevant drivers in this case are land occupation, the effect of global warming on terrestrial ecosystems and terrestrial acidification (Crenna et al., 2019).

Taking into account the overall impact of global supply chains on the environment, FAO estimated that around 7% of global GHG emissions can be attributed to food loss and waste only. To produce the food that is either lost or wasted, around 30% of global agricultural land surface and 6% of the total water withdrawn are used (FAO, 2019). In Europe, around 15% of the overall impact of consumed food can be attributed to food waste, which is dominated by cereal products by mass. Impact of cereals is however outweighed by animal products. Scherhaufer et al. (2018) attribute around 56 million t CO_2 eq to beef waste and 25 million t CO_2 eq to cereal waste in Europe in 2011, with the amount of cereal waste reported almost twenty times higher than bovine meat waste. Food primary production carries approximately between 70% and 95% of the overall impact, depending on the considered impact category. Food processing, retail and distribution, consumption and disposal equally share the remaining percentage (Scherhaufer et al., 2018). Other studies at country level show comparable results. In Germany, impact share of food waste on the entire supply chain has been quantified between 13% and 20% with heavier burden attributed to dairy products and meet (Eberle and Fels, 2016). These categories dominate also the impacts of supermarket food waste in Sweden, along with cereal products (Brancoli et al., 2017).

2.3. Reducing food waste amount and environmental burdens

With the aim of reducing the environmental impacts of food supply chains, concrete measures to reduce food waste amount are necessary. In Priefer et al. (2016) a thorough analysis is made on the policies implemented in recent years in Europe to tackle the problem of food waste. The authors discuss the introduction of regulatory measures (e.g. mandatory targets for food waste reduction, taxation schemes for waste treatment), economic measures (e.g. short supply chains for agricultural products), and voluntary initiatives (e.g. voluntary commitments by producers and consumers, food donation, communication and labeling).

All the examples reviewed by Priefer et al. (2016) are in line with the last amendments of the European Waste Framework Directive and with the principles of sustainable production and consumption which prioritize food waste management initiatives aimed primarily at prevention, followed by reuse, recycle, recovery, and ultimately disposal (European Parliament and Council of the European Union, 2008; Papargyropoulou et al., 2014). Sustainable production implies that at the first stages of the food supply chain waste is prevented by food surplus and overproduction control, in addition to technological improvements and knowledge transfer, especially in developing countries (see section 2.1). In distribution and consumption, food availability should not exceed what is actually needed for food safety and surplus should be redistributed to people whose access to basic nutrition is more difficult (Papargyropoulou et al., 2014). Raising consumer awareness is also important to promote better meal planning in terms of food quantity and typology. In this regard, shifting to more vegetable and fruit rich diets would not necessarily reduce food waste quantity since these food categories generate usually high amount of avoidable waste, but in general fruit and vegetables production have less impact on the environment compared to animal products (Nemecek et al., 2016; Poore and Nemecek, 2018; Sinkko et al., 2019). Another option for waste prevention is represented by improving packaging technologies to maximize the shelf life of perishable products (Heller et al., 2018; Molina-Besch et al., 2019; Nemecek et al., 2016). Following the principles of waste hierarchy, recycling food waste into animal feed and compost is a good option when prevention is not possible. Finally, energy recovery (e.g. anaerobic digestion, incineration) and landfilling are to be preferred only as a last choice (Papargyropoulou et al., 2014).

Notwithstanding the long list of solutions proposed to reduce food waste, the debate on their effectiveness is still very much alive. For instance, Mourad (2016) reconducts the topic to the broader discussion about strong and weak sustainability of production and consumption systems (O'Rourke and Lollo, 2015), arguing that prevention based solely on efficiency optimization is weak because it often depends on voluntary commitments that are nonetheless subordinate to economic profit and to the preservation of food markets status quo. Strong waste prevention measures would imply a substantial simplification of commodity chains, enhancing economic and social relationships between producers and consumers, and reconciling consumption patterns with natural cycles. Provided that the efficiency of alternative food systems has to be greater than that of large-scale industrial systems to get significant environmental benefit (Nemecek et al., 2016). Similarly, measures that foresee technological improvements in food conservation through improved packaging or an increase in the efficiency of waste energy recovery or treatment should also be considered less effective than a radical reformulation of production and consumption paradigms (Bernstad Saraiva Schott and Andersson, 2015).

2.4. Food surplus redistribution

Food redistribution is defined as a process by which surplus food *is recovered, collected and provided to people, in particular to those in need* (EC, 2017). The evaluation of existing and prospective measures to lower the environmental consequences of food waste generation is carried out by many authors. However, the majority of studies in the literature focus on optimizing the technological aspects of waste treatment or comparing different valorization and treatment technologies, i.e. anaerobic digestion, incineration, composting and landfilling (e.g. Ahamed et al., 2016; Bernstad and La Cour Jansen, 2012; Bernstad Saraiva Schott et al., 2016;

Salemdeeb et al., 2018; 2017; Vandermeersch et al., 2014). Other authors discuss the environmental benefit of food waste prevention and minimization (e.g. Bernstad Saraiva Schott and Andersson, 2015; Oldfield et al., 2016; Sinkko et al., 2019; Tonini et al., 2018), and environmental impact of surplus food donation is explicitly quantified in fewer studies (Albizzati et al., 2019; Beretta and Hellweg, 2019; Eriksson et al., 2015; Eriksson and Spångberg, 2017; Moult et al., 2018).

Albizzati et al. (2019) assess the carbon footprint of food waste management options for fruit and vegetables in the French retail sector, comparing food redistribution with incineration and energy recovery, anaerobic digestion, and conversion. In Eriksson et al. (2015) and Eriksson and Spångberg (2017) donation of food waste from Swedish supermarkets is compared with prevention, incineration, anaerobic digestion, composting, landfilling, and animal feed production. Impact of waste from food retailing is also investigated by Moult et al. (2018) for the same management scenarios. Furthermore, Beretta and Hellweg (2019) examine the food service sector and discuss a case study where restaurant food is donated, showing advantages in terms of GHG emissions and potential biodiversity loss. Overall, the aforementioned studies confirm the priority levels of the waste management hierarchy supporting prevention and donation over the other options. Finally, other studies concern food donation systems considering also its economic and social dimensions (Reynolds et al., 2015; Vittuari et al., 2017). Below we present a new case study about the environmental assessment of food donation in Italy through one of the most widespread charitable networks in the country.

3. Material and methods

3.1. Outlining a case study: the Italian setting

In Italy, different studies quantified food waste. According to Vulcano and Ciccarese (2018), about 2 Mt of food were wasted in 2005–2006 by agri-food industry with the higher quotes in the processing and conservation of fruit and in the dairy sector. Approximately 400 000 tons of food were wasted by the distribution stage, 40% of whom represented by fruit and vegetables. In 2014, 1.19 Mt of food were wasted, and an Italian family threw away an average of 49 kg of food every year. Fruit and vegetables represented the major fraction. In the present study, food waste from retail and distribution is taken into account, representing between 8% and 13% of the total food waste in Italy (Vulcano and Ciccarese, 2018). Surplus food is redistributed through “solidarity emporiums”. These charities redistribute essential goods to the poor and sustain personal empowerment and social integration. Emporiums support families in economic distress, especially those with children under 24 months.

This work is focused specifically on the charities located in the Veneto Region (northeastern Italy) in 2017, supported by private citizens and clerical associations, and regulated by the Regional Law November 2011 on surplus food redistribution (Veneto Region, 2011); in 2017, people who took advantage of these initiatives were about 133 000 and the emporiums received funding for 490 000 euros (Veneto Region, 2017). From an organizational point of view, the emporiums can be classified as “direct” and “indirect”: the first ones are like supermarkets, where people can directly exchange their credits to get food, whereas the second ones are storehouses that deliver food surplus to direct emporiums.

In 2017, in the Veneto Region there were twelve solidarity emporiums plus the regional office of the Italian Food Bank Network “Banco Alimentare”, located as shown in Fig. 1. Five direct emporiums plus the Italian Food Bank are located in the province of Verona, one indirect emporium in the province of Padua, three emporiums, two direct and one indirect, in the province of Venice, and three emporiums, two direct and one indirect, in the province of Treviso (Appendix 1, section 1).

In this article, we quantify the food recovered by selected solidarity emporiums from producers and retailers. Afterward, we apply Life Cycle Assessment (LCA) to our case study to assess environmental burdens of surplus food redistribution. LCA is a quantitative and comparative standardized methodology to assess potential environmental impacts along the life cycle of products and services (International Organization for Standardization, 2006a, 2006b). All methodological choices and assumptions taken in the LCA study are detailed in the next section.

3.2. Life cycle assessment of surplus food redistribution

3.2.1. Definition of the goal and scope of the study

The LCA goal is to evaluate the environmental impact of a local food redistribution system intended as a service whose reference flow is represented by the food basket recovered by each emporium and redistributed. The study is carried out on food waste disposal and recovery scenarios according to the system boundaries in Fig. 2. It is assumed that potential further food waste from scenario 1 is negligible and all recovered food is consumed for two reasons. First, because the food offer in emporiums is closer to demand since those who benefit from this service prefer it to traditional commercial circuits and, on the other hand, tend to receive quantities in line with their needs. Second, because emporiums manage smaller food flows than large retailers and are usually more efficient in terms of waste.

The functional unit of the study is 1 kg of surplus food redistributed by each emporium up to the gate (scenario 1), or alternatively sent to incineration, anaerobic digestion, and composting (scenario 0). We use 2017 data for the emporiums, the most recent available, and data on the same year for regional municipal organic waste management (incineration: 15%; for the remaining percentage, anaerobic digestion: 49%, composting: 51%; Franz et al., 2018; Tua et al., 2017).

The life cycle impact assessment (LCIA) method used is ReCiPe, hierarchist (Huijbregts et al., 2016). The study considers all the indicators at midpoint level as reflecting the complexity of food production systems and management alternatives related to the food baskets recovered. For the analysis of the two scenarios an attributional approach (ALCA) and a consequential approach (CLCA) have been applied, the latter considering in scenario 1 the avoided food production and waste treatment impact, deriving from satisfying local food demand with recovered food rather than with an equal quantity of additional food produced. Given the great variability in the food categories recovered from the emporiums, the impacts of an average food basket are also assessed in section 4 according to CLCA. It is therefore assumed that the diversity of recovered food in the region reflects that of the average food basket. A consequential approach is also applied by Albizzati et al. (2019), and Eriksson and Spångberg (2017) where the authors considered however donated food as a substitute of cheaper alternative food in system expansion (e.g. bread). Net environmental benefits of food redistribution (i.e. avoided impacts of food production and disposal) are evaluated as well by Caldeira et al. (2019b).

3.2.2. Inventory data collection, modeling and LCA interpretation

Primary data on recovered food and emporiums' activities were collected from each charity. Specifically, requested data were the supplier and consumption of electricity, consumption of heating fuel, water consumption, type and quantity of detergents used, number of cold rooms, refrigerant gas used and recharged quantity, mode of transport of food surpluses and characteristics of the

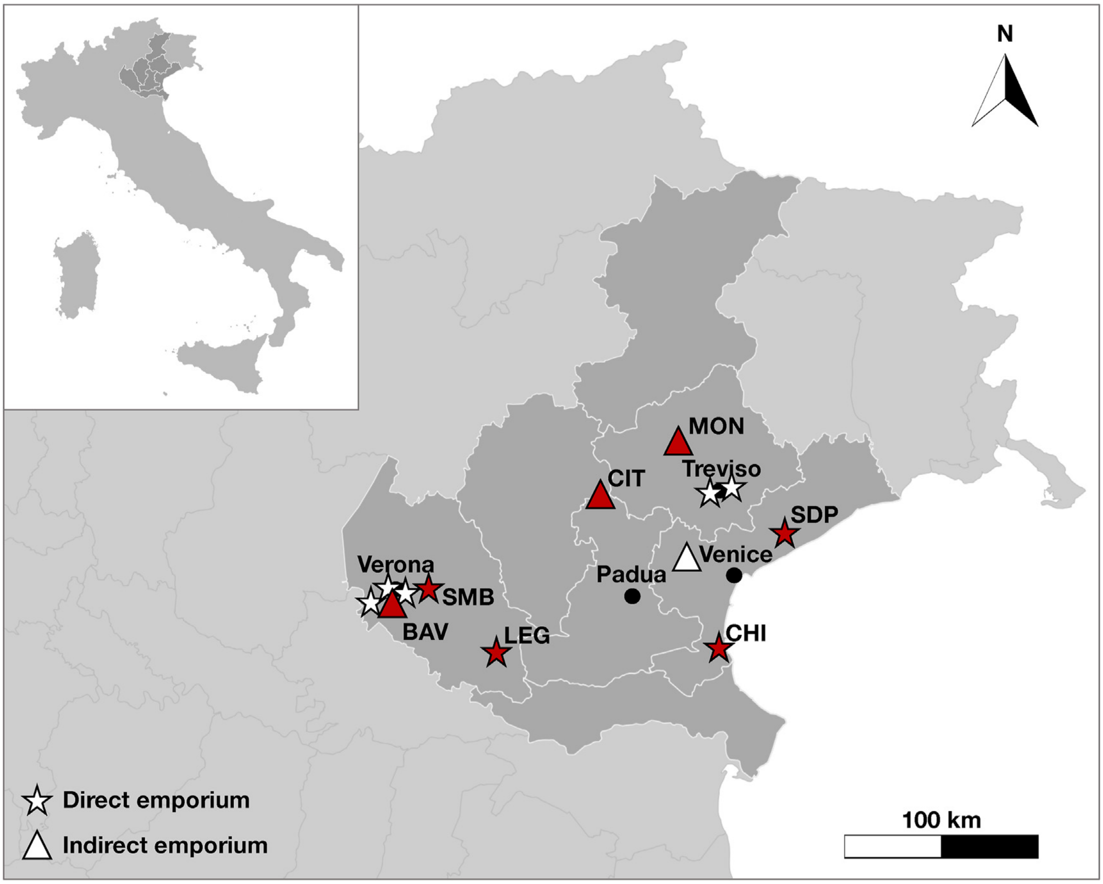

Fig. 1. Direct and indirect emporiums of the Veneto Region. Charities who provided reliable data for the study are marked in red. BAV: Banco Alimentare di Verona; SMB: San Martino Buon Albergo; LEG: Legnago; CIT: Cittadella; MON: Montebelluna; CHI: Chioggia; SDP: San Donà di Piave. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

vehicles used, quantity and type of surpluses recovered and their place of origin. In the absence of the latter, the kilometers travelled, or the total fuel consumption were requested. Since most of the emporiums' staff is made up of volunteers and centralized systems to monitor emporiums' activities are usually not available, data collection has proved to be difficult, especially with regard to technical data, such as the electricity and refrigerant gas consumption of the cold rooms, but also to food waste received from supermarkets and producers, and redistributed. Another limitation was that many emporiums use buildings under concession from institutions or religious associations, and therefore were not able to retrieve the requested information directly. For these reasons, six emporiums were excluded from the LCA study due to lack of reliable and sufficient information. Fig. 1 shows the seven emporiums retained in the study: Banco Alimentare di Verona (BAV), San Martino Buon Albergo (SMB), Legnago (LEG), Cittadella (CIT), Montebelluna (MON), Chioggia (CHI), San Donà di Piave (SDP). In case of incomplete data, some assumptions are made in Table 1 for modeling.

The databases used to model food products are Ecoinvent v3.3 (Wernet et al., 2016) and Agri-footprint v2.0 (Durlinger et al., 2014) or LCA food (Nielsen et al., 2003), for processes not available in Ecoinvent (see Appendix 1, section 2, for the processes used). Fish products are taken from LCA food as well as cold chain data for kg of frozen products (electricity and heat in wholesale and supermarket). Given that some products are modeled in both Ecoinvent and Agri-footprint, a sensitivity analysis is also carried out in section 4.4 to assess the differences in life cycle impact assessment results, deriving from using processes coming from the two databases for the most relevant food products.

Since the LCA is performed on a service, represented by the management of a surplus food basket, rather than on single food products, secondary data for food are used. This implies not considering the impact of specific food production processes, having necessarily less detailed results on single food or food categories. However, differentiating the impact of specific life cycle stages of food products is out of the scope of the study. For our purposes, the interpretation of results and the impact contribution analysis is carried out for all impact categories considering aggregated food types, surplus food transport to the emporiums or to waste treatment sites, waste treatment processes, electricity and water consumption of the emporiums.

4. Results and discussion

4.1. Surplus food recovered

In the reference year, the charities included in the study recovered about 2 800 t of surplus food from retailers and producers. The quantities are highly differentiated between emporiums, as shown in Table 2, with a maximum of 1 900 t for the Italian Food Bank and a minimum of 1.9 t for CHI. It should be noted that indirect emporiums of MON and BAV collected the largest amount of donations and redistributed the food to smaller emporiums. In addition to what reported in Table 2 for CHI, this emporium received 3.6 t of fruits and vegetables from MON. The latter

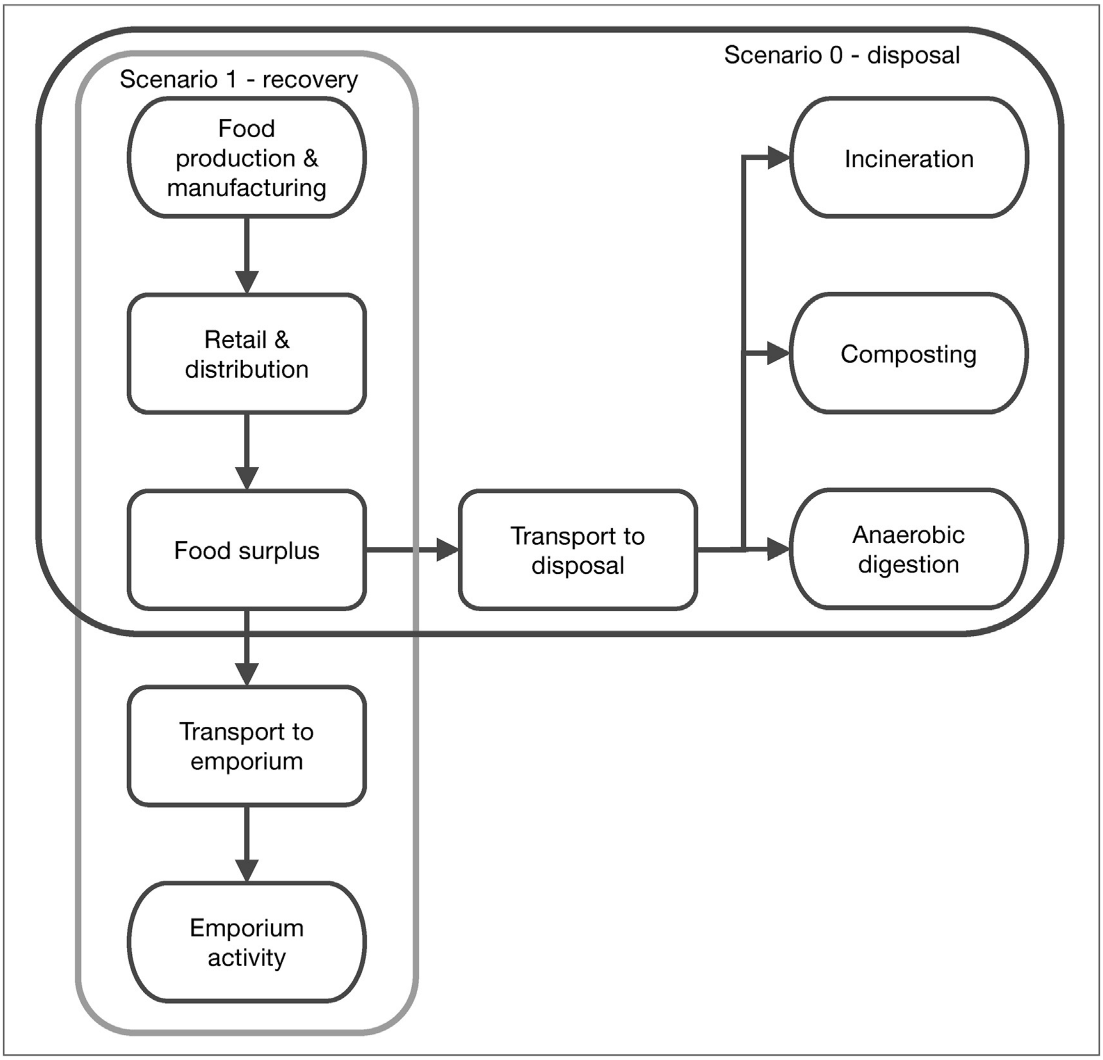

Fig. 2. System boundaries and scenarios of the LCA.

redistributed also 0.6 t of fruit and vegetables to CIT and 10.1 to SDP, which received another 9.8 t from BAV. To avoid double counting surplus food recovered from indirect emporiums and delivered to direct emporiums, these quantities are associated to indirect emporiums only. This allows also to allocate properly fuel consumption of the transport between indirect and direct emporiums to the first ones in charge of the delivery.

A significant difference is also evident with respect to the types of food donated. Not all categories are present in each emporium. Fruit and vegetables are the most abundant in all charities except SMB and the percentage on the total food surplus ranges from a minimum of 20.6 (SMB) to a maximum of 100 (LEG). Cereal derivatives are the second category (2.3%–31%), dairy products the third (for SMB is the first food category recovered) and meat and fish the last one. Other food includes water, soft drinks, colonial goods (e.g. cocoa, sugar, spices), eggs, animal and vegetable fats, and ready meals.

4.2. Attributional approach and impact contributions

The impact of each emporium is significantly different and correlated to the type of food donated (Fig. 3). Comparing the emporiums in scenario 0, food recovered by SDP that is sent to disposal has the greatest impact in all impact categories except freshwater and marine ecotoxicity, where LEG has the major impact, and water depletion where water consumption for fruit and vegetables in MON drives the impact (Appendix 1, section 3). The higher impact in SDP is mostly due to the high percentage of animal products (39.2%) and specifically meat and fish (14.4%) compared with the food recovered by the other charities (e.g. CHI, LEG, CIT, MON).

The attributional approach narrows the assessment to the analysis of the difference between the waste treatment impact of discarded food and the operating phase impact of the emporiums, including the transport to the waste treatment facilities or to the emporiums respectively. For this reason, even if scenario 1 shows in general better environmental performance, the results do not unequivocally favor food donation, for example considering land occupation and transformation, since land use for the production of additional food is not considered in ALCA (Fig. 3). An exception is represented by freshwater and marine ecotoxicity where food waste treatment has much higher impact than surplus food recovery by all emporiums. For instance, between scenario 0 and 1 freshwater ecotoxicity differs by one order of magnitude for MON (5.57E-02 and 5.08E-03 kg 1,4-DB eq) and CIT (5.06E-02 and 5.86E-03 kg 1,4-DB eq). In these cases, incineration contributes alone to

Table 1
Assumptions made to build the model on data collected from the emporiums.

Data	Assumptions
Cold rooms and refrigerant gas	Only BAV was able to indicate all the information requested, asserting that the reintegrated gas quantity was zero. Out of the remaining emporiums some have no refrigerated rooms, in some others they are not used or there are small refrigerators, i.e. containing less than 3 kg of refrigerant gas, and therefore not subject to fluorinated gas regulations, concerning the containment, use, recovery and distribution of fluorinated gases requiring annual checks starting from 3 kg (EC, 2014). As a result of these considerations, it was decided to use the data provided by BAV also for all the other emporiums, assuming therefore no refrigerant gas consumption.
Electricity consumption	Ecoinvent v3.3 contains average data for the 2014 Italian electricity mix. New processes have been created using mix data from local energy suppliers. When emporiums did not provide information on their electricity suppliers, or when it was not possible to retrieve data on the operator's energy mix, 2017 national data from the Italian authority for energy (GSE) have been used (this was the case for the CHI emporium).
Fuel consumption	For all the emporiums analyzed, the heating system is connected to the electrical system. The data of the heating fuel were therefore included in the electricity consumption.
Detergents and water consumption	SDP and CIT did not provide data on water consumption, as it was considered negligible. BAV and LEG were unable to find information on the detergents used. In this case, it was decided to proceed as follows: the emporiums that provided the data for water and detergents consumption were first modeled and the impact was found to be irrelevant on the total. For this reason, water consumption and detergents have been excluded from the analysis.
Recovered food	While some emporiums indicated quantities of specific products, most of them indicated quantities related to macro categories of food, without specifically reporting the type of products. Below the details of each emporium: • CHI and MON reported specific data for the types of food products recovered and therefore it was not necessary to make any assumption. • BAV provided an excellent level of detail, with a high number of macro-categories, including "meat", "fish", "oils and seasonings", "fresh and dairy products". However, there were also items that did not refer to any macro-category. In this case, the following assumptions were made: "other fresh and frozen meat" were modeled as poultry, since the remaining surpluses of the macro-category "meat" concerned pork and beef; "other frozen" have been split in half between frozen fish and frozen bread; "mixed fresh food" have been distributed equally between the products listed under the category "fresh and dairy products"; for "vegetable fats" other than olive oil the choice went to sunflower seed oil, as it is the most traded in Europe in retail and food services (EC, 2019). Since the database does not contain the Italian production process, we decided to use the Ukrainian process, as it is the largest producer in Europe (FAOSTAT – FAO, 2020). The remaining data on the type of food recovered, despite being very accurate, still required a series of assumptions because within the databases it was not always possible to find the reference process. For example, dry and fresh pasta, pizza, biscuits, pastries and other cereal derivatives were modeled as bread assuming wheat as the main ingredient in weight and using bread cooking as a generic industrial cooking process. Moreover, generic spices were modeled as coffee, partly because listed together with coffee and partly because it was not possible to find inventory data for specific spices. Within the macro category "fruit", some types of product were clearly indicated (e.g. apples, clementines, pears, peaches and kiwis) while others were simply reported as "fresh fruit". To include the latter, it was decided to use a mix of fruits recovered from the emporium of MON, namely peaches, nectarines, plums, apricots, oranges, pears, watermelons, apples, kiwis, modeling a category called "fruit mix". "Fruit juices" and "preserved fruit" were modeled as "fruit mix" since fruit cultivation is assumed to be the most relevant stage of the life cycle in comparison with the following industrial processes. The same reasoning has been made for the macro category vegetables and legumes. For the first ones, it was decided to use a mix of vegetables recovered again from MON (carrots, salad, peppers, tomatoes, cucumbers). For the second ones, the most consumed legumes in Italy were chosen, namely lentils, beans, chickpeas and peas (Italian Ministry of Agricultural Food and Forestry Policies, 2020). Finally, quantities of ready-to-serve soups and homogenized, usually composed of dried pasta and legumes and fruit or chicken respectively, were equally divided in and modeled as fruit, vegetables and legumes, chicken and bread. • SDP, LEG and SMB: the same assumptions made for BAV were applied to these emporiums. • CIT: for this emporium multiple assumptions were necessary, since for some products data were provided only as outgoing donation and not as recovered surplus. In this case, the outgoing quantity was considered equivalent to the recovered quantity. In addition, there were difficulties with the units of measurement, since most of the data were provided in "packages" or "cassettes". Only in the case of apples and pears it was reported that 15 packages were equivalent to 225 kg and in the case of tomatoes 1 package was 1.5 kg. Such weights were used also for fruit and vegetables. It is important to underline that indirect emporiums deliver surplus food to direct emporiums. To avoid double counting of the quantities recovered, the products that the direct emporiums have received from indirect emporiums were attributed to indirect emporiums only.
Transport	Only CHI and MON reported the quantities transported in each trip from the place of origin of the surplus to the emporium; it was thus possible to adequately calculate the kgkm. CIT, LEG, SDP and SMB provided data on the amount of fuel consumed in 2017 and on the l/km that can be covered with their fleet to calculate the km travelled. BAV used three means of transport to recover surpluses, and for each one it indicated the total fuel consumption and l/km. However, it did not indicate the quantity of food transported by each vehicle. Therefore, to calculate the kgkm it was assumed that the heaviest vehicle carried 60% of the surplus recovered, and the remaining 40% was equally divided between the remaining two (equally weighting) vehicles.
Disposal scenario	Three types of disposal technologies were included in one scenario: incineration, anaerobic digestion and composting. The waste streams were divided as follows: 15% to incineration, for the remaining 85%, anaerobic digestion 49% and 51% composting (Franz et al., 2018; Tua et al., 2017). It was assumed that the surpluses with packaging went directly to the incinerator, while the surpluses without packaging were sent to anaerobic digestion and composting (Veneto Regional Environmental Protection Agency – ARPAV, personal communication). In order to calculate the kilometers travelled to the disposal site, it was assumed that most of the surpluses occurred in supermarkets, which are mainly located in provincial capitals. An average of the distances between disposal plants (the list of which was provided by ARPAV for composting and anaerobic digestion, and by the Higher Institute for Environmental Protection and Research – ISPRA, for incineration) and related provincial capitals was then used.
Packaging	In modeling recovered food, packaging was not considered since it was assumed to account for only 2% in weight, as reported by Albizzati et al. (2019).

around 77% of the total and anaerobic digestion of biowaste to 14%. For all impact categories, impact contributions to scenario 0 and 1 are described below (for detailed results see Appendix 1, sections 3 and 4).

Climate change. GHG emissions are mainly produced by the dairy and meat supply chain, including soybean production for animal feed. In the emporiums where more animal products are collected (SDP and SMB), their relative impact ranges between 30% and 70% of the total in scenario 0. In the same scenario, the average contribution of waste treatment processes is about 14%. Scenario 1 includes the impact of logistics for surplus food collection which accounts for an average of 26% GHG emissions.

Ozone depletion. The most relevant activities contributing to ozone depletion are connected to transportations both in scenario 0, which includes municipal waste collection, and in scenario 1. In the latter, refrigerated lorries are also used by BAV. After logistics,

Table 2
Surplus food quantity recovered and product categories percentages. Food reported for indirect emporiums BAV and MON include those redistributed to direct emporiums CHI, SDP, and CIT.

Emporium	Surplus food recovered (kg)	Cereals	Fruit and vegetables	Dairy	Meat and fish	Others
BAV	1 895 809	26.6	38.0	7.5	0.8	27.2
CHI	1 893	7.6	92.4	–	–	–
SDP	24 366	28.9	30.3	24.8	14.4	1.7
SMB	63 600	23.9	20.6	25.6	4.9	0.2
MON	799 131	2.3	95.5	1.8	0.3	0.2
CIT	14 569	31.0	63.8	–	1.2	4.0
LEG	9 000	–	100.0	–	–	–

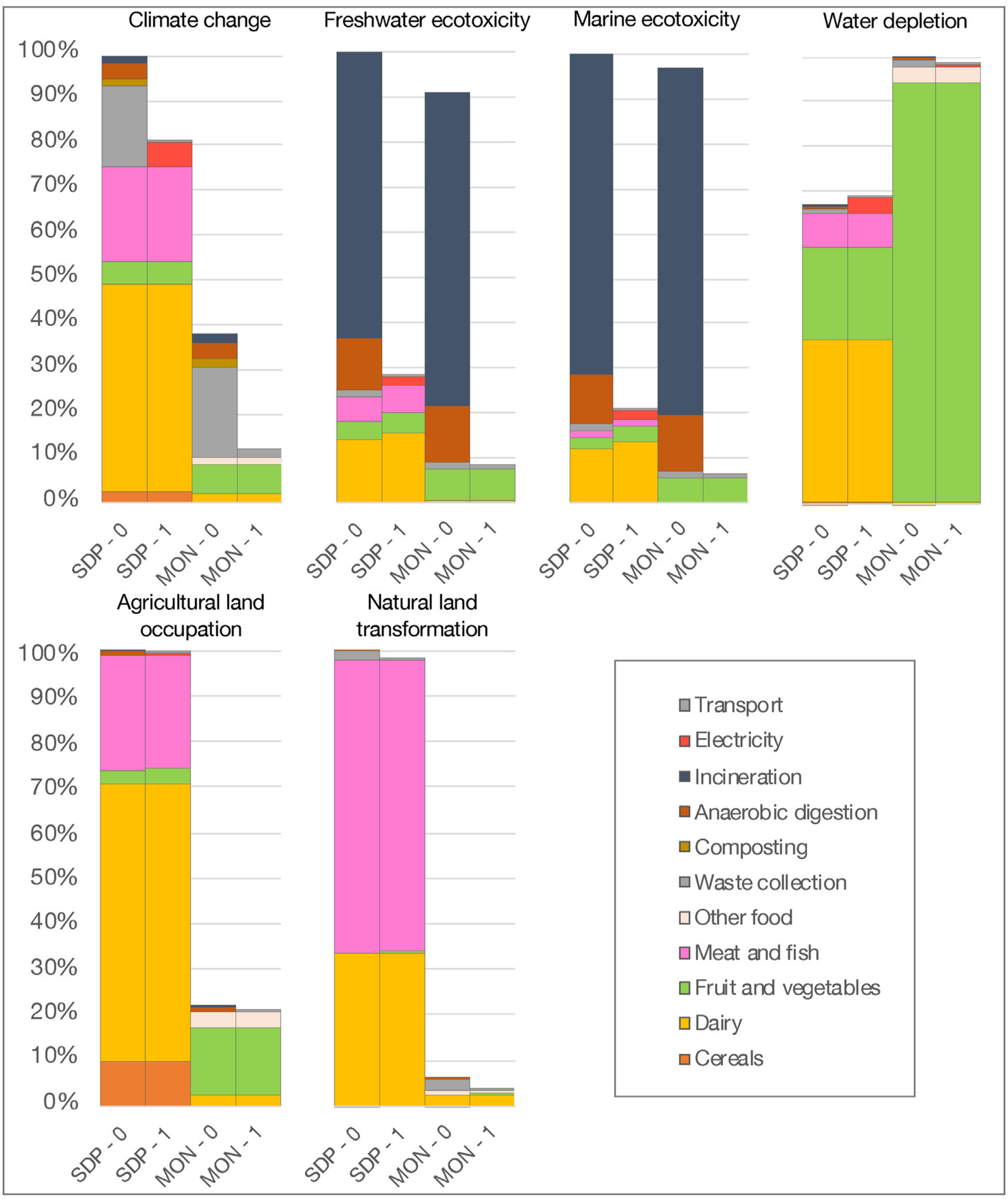

Fig. 3. Life cycle impact assessment results and impact contributions in ALCA applied to 1 kg of food wasted (scenario 0) and redistributed (scenario 1) in the SDP and MON emporiums. Detail for climate change, freshwater and marine ecotoxicity, water depletion, agricultural land occupation, and natural land transformation. See Appendix 1 for further results.

impact of frozen food is the second most significant factor affecting this impact category with an average of 18% of the overall kg CFC-11 eq released.

Terrestrial acidification. Around 33% and 26% of the total kg SO_2 eq produced in the two scenarios are associated respectively to waste collection and food redistribution. The supply chain of dairy products accounts for 23% and agricultural activities to produce fruit, vegetables, and cereals contribute the 19% of this impact category.

Marine and freshwater eutrophication. Nutrients emissions to freshwater and sea water are associated with the cultivation of fruit and vegetables (20% of the total kg P eq to freshwater and 13% of the total kg N eq to sea water) and with the dairy industry (15% of the total kg P eq to freshwater and 34% of the total kg N eq to sea water), including feed cultivation. In scenario 0, an average of 43% contribution to freshwater emissions is due to biowaste treatment by anaerobic digestion and digester sludge treatment.

Human toxicity. 37% of the kg 1,4-DB eq in scenario 0 are related to anaerobic digestion and incineration whereas 34% is associated to logistics in scenario 1. Dairy products are again relevant in this impact category with an average contribution of 35%.

Photochemical oxidant formation. Waste collection in scenario 0 and transport for surplus food collection in scenario 1 drive non-methane volatile organic compounds (NMVOC) emissions. Contributions are 73% and 46% of the overall impact respectively. Moreover, between 3% and 20% of total NMVOC emissions are associated with dairy products.

Particulate matter formation. The same drivers of photochemical oxidant formation have a relevant contribution also in particulate matter formation, with slightly different percentages. Collection of food waste weights an average 48% on the overall impact of scenario 0 and transport for food redistribution have a 34% share of kg PM_{10} eq emissions in scenario 1. The average contribution of the dairy industry in this impact category is 22%.

Terrestrial, freshwater, and marine ecotoxicity. While the average percent contribution of the dairy supply chain is comparable to the previous impact category for terrestrial ecotoxicity, the impact of herbicides and pesticides used in agricultural activities has a greater contribution (62% of the total kg 1,4-DB eq), mainly related to the cultivation of carrots and strawberries. More than 70% of the impact on freshwater and sea water is due to incineration in scenario 0, whereas in scenario 1 a contribution between 20% and 30% is attributed to surplus food collecting.

Ionizing radiation. Electricity imports from France and Switzerland drive the impact category with an average contribution of 18% considering all emporiums and a peak of 88% associated with CHI. The remaining, relevant processes are related to transport of food waste or food recovery and linked to the production of fuels and vehicles.

Land use. Around 30% of agricultural land occupation is associated to the dairy supply chain, while the remaining 70% is almost equally distributed between fruit, vegetables, legumes and cereals. Urban land occupation, on the other hand, is almost entirely attributed to transport processes which include road construction. The transformation of natural land is linked to both feed cultivation for the meat and dairy industry, and transport.

Natural resources depletion. A great percentage of water is depleted for fruit and vegetables cultivation (e.g. 19% apricots, 17% peaches), and around 30% depletion is associated with dairy products. Metal depletion is mainly due to vehicles production and therefore to transport of food waste and food recovery in the two scenarios. These activities drive also the depletion of fossil resources.

4.3. Consequential approach and net environmental benefit

Including avoided food production and disposal in the analysis highlights the significant benefits of surplus food recovery and redistribution (see Appendix 1, section 5). However, as in the previous section, also in CLCA the results show that scenario 1 is not advantageous for all the emporiums in all impact categories. Scenario 0 performs better for CHI and LEG considering ionizing radiation, fossil depletion, metal depletion and urban land occupation. In the latter impact category, slightly better values for scenario 0 are also identified for BAV, SMB, and CIT. As discussed above, these results reveal the importance of emporiums efficiency from the point of view of energy consumption and logistics organization, especially in relation to the amount of surplus food recovered. 1 893 kg of food recovered by CHI and 9 000 kg by LEG are relatively low quantities compared to the other charities, and thus transport and energy consumption allocated to 1 kg of food donated appear to be much more relevant, also including avoided food production and disposal in the system.

The variability of recovered food and efficiency of the different charities gives a representation of the heterogeneity of food donation mechanisms at the regional level. To provide the reader with a general overview of the impact of surplus food redistribution, we show in Table 3 the impact averages of all emporiums in scenario 0 and 1 (CLCA), along with the net environmental benefit (i.e. the difference between scenario 0 and 1). Even considering some inefficiencies of a few emporiums, as discussed above, average results of scenario 1 perform better than scenario 0 in all impact categories except for urban land occupation, where increased transport makes LEG-1 m^2a five times bigger than LEG-0 (Appendix 1, section 5) affecting average results. The net environmental benefit of food donation compared to scenario 0 is 1.9 kg CO_2 eq for each kg of surplus food redistributed. Avoided impact of food production also bring significant benefit in terms of agricultural land occupation (1 m^2a per kg of food) and fossil resource depletion (0.3 kg oil eq). Photochemical oxidant formation, freshwater and marine ecotoxicity have the major benefits resulting from a reduction of much more than 100%.

4.4. Limitations

The most significant difficulty encountered in conducting the study was related to data collection. Data quality is fairly good, especially for larger emporiums where the level of detail is very high. However, the way data were collected, and their form was not uniform and in some cases some assumptions had to be made regarding the composition of recovered food waste (Table 1). Another important limitation is related to the databases used to model the emporiums. Specific food production processes for Italy are not available in Ecoinvent and Agri-footprint. Nevertheless, adopting the same modeling choices for all actors and scenarios in a comparative study, even with some degree of uncertainty, could still provide a realistic description of their relative impacts. Some difference may arise when a choice has to be made between the same product modeled in different LCA databases, and between emporiums that have that specific product or not. To test the sensitivity of different modeling options, dairy products, one of the most relevant food categories in our study, have been modeled in SMB and SDP using processes from Ecoinvent and Agri-footprint (Appendix 1, section 6). The comparison between scenario 0 and scenario 1 for the same emporium does not change, the objective of the study is therefore reached regardless of the type of model used and although the results may be quite different for some impact categories. The impacts of the two emporiums relative to those who did not receive donations of dairy products (CHI, CIT, LEG) does not

Table 3
Average impacts and net environmental benefit of 1 kg of food donated according to CLCA approach.

Impact category	Unit	Scenario 0	Scenario 1	Net benefit
Climate change	kg CO_2 eq	1.81E+00	−6.49E-02	1.87E+00
Ozone depletion	kg CFC-11 eq	1.84E-07	4.28E-08	1.41E-07
Terrestrial acidification	kg SO_2 eq	1.24E-02	−3.71E-04	1.28E-02
Freshwater eutrophication	kg P eq	4.53E-04	−3.59E-05	4.89E-04
Marine eutrophication	kg N eq	5.11E-03	−1.18E-04	5.23E-03
Human toxicity	kg 1,4-DB eq	2.49E-01	1.16E-01	1.34E-01
Photochemical oxidant formation	kg NMVOC	9.78E-03	−3.39E-03	1.32E-02
Particulate matter formation	kg PM_{10} eq	3.80E-03	−2.13E-04	4.02E-03
Terrestrial ecotoxicity	kg 1,4-DB eq	1.72E-02	1.62E-06	1.72E-02
Freshwater ecotoxicity	kg 1,4-DB eq	4.93E-02	−3.48E-02	8.41E-02
Marine ecotoxicity	kg 1,4-DB eq	4.44E-02	−3.26E-02	7.70E-02
Ionizing radiation	kBq^{235}U eq	8.22E-02	5.85E-02	2.37E-02
Agricultural land occupation	m^2a	9.98E-01	5.71E-03	9.92E-01
Urban land occupation	m^2a	1.44E-02	1.64E-02	−2.00E-03
Natural land transformation	m^2	2.48E-03	−2.64E-05	2.51E-03
Water depletion	m^3	6.19E-02	8.99E-02	5.29E-02
Metal depletion	kg Fe eq	3.12E-02	2.84E-02	2.83E-03
Fossil depletion	kg oil eq	3.51E-01	4.86E-02	3.02E-01

change significantly enough to overturn the results. Important differences are nevertheless evident with regard to terrestrial acidification, urban land occupation and metal depletion. The Agrifootprint processes result in higher terrestrial acidification impact due to larger quantities of ammonium-based fertilizers modeled. On the other hand, Ecoinvent processes take into account the provision of infrastructures and buildings linked to the supply chain, which have an impact on urban land occupation and metal depletion.

The CLCA results describe more comprehensively than ALCA the environmental consequences of food recovery, considering the avoided impact of additional food production and disposal to meet food demand. However, the study does not take into account the effect on the market of an increase in biogas (used for heat and electricity production) and compost that would be produced in scenario 0 if surplus food was not recovered. In the region, in 2017 694 000 t of organic waste have been sent to anaerobic digestion and composting. From this amount, 250 000 t of compost, 57 millions Nm^3 of biogas and 129 GWh of electricity have been produced, including self-consumption (Franz et al., 2018). This equals 0.36 t of compost, 82.13 Nm^3 of biogas and 185.88 kWh of electricity per 1 t of organic waste. On this basis, 2 387.11 t of surplus food sent to composting and anaerobic digestion (85% of the total according to our disposal scenario) would produce 859.36 t of compost, 196 053.34 Nm^3 of biogas and 443.72 MWh of electricity. It remains difficult, however, to estimate how the market would change and which products would be replaced by these amounts of compost (e.g. another fertilizer with the same nutrient content) and biogas (e.g. natural gas for domestic heating, automotive fuel).

5. Conclusions

In this study, food waste is represented by products suitable for human consumption that are sent to disposal because they do not meet manufacturer or customer specifications, or because they remain unsold by retailers. Food primary production linked to agricultural and especially animal products has the greatest environmental impact along food supply chains, as illustrated in section 2. After preventing food waste in the production stage, surplus food donation can be an effective way to limit the burden of these impacts.

The article presents the results of a study carried out at territorial level on mechanisms for the collection and redistribution of surplus food by solidarity emporiums. The quantity of recovered food is very variable (from 2 t in CHI to 2 000 t in BAV) as well as the typology (almost 100% fruit and vegetables in LEG and MON or more uniformly distributed between food categories in SDP). The attributional approach emphasizes in particular the difference between the impacts of the collection and treatment of food waste, and those of the collection and redistribution of surplus food by emporiums, which are usually lower. Incineration carries considerable burden mainly on toxicity, anaerobic digestion on freshwater eutrophication, and composting on climate change. At the same time, waste collection has a significant weight on several impact categories and up to 80% of the overall impact on fossil depletion, ozone depletion, and photochemical oxidant formation (e.g. MON-0, CHI-0, CIT-0, see Appendix 1, section 4). On the other hand, the cumulative impact of food transport and electricity consumption in scenario 1 is typically lower than waste collection and treatment in scenario 0 (Fig. 3).

The consequential approach, considering avoided impacts of additional food production and disposal to satisfy food demand, highlights a significant reduction of potential environmental impacts made possible by the implementation of a territorial network of emporiums. Average reduction is above 100% for several impact categories (e.g. climate change, terrestrial acidification, freshwater eutrophication, photochemical oxidant formation) and reaches around 170% for freshwater and marine ecotoxicity, due to avoided waste incineration mainly. The results of CLCA are comparable with existing studies that adopted similar approaches, even though in different contexts. For instance, considering global warming potential Eriksson and Spångberg (2017) report an average avoided impact of 0.6 kg CO_2 eq/kg of food donated (only fresh fruit and vegetables). In Albizzati et al. (2019) the impact reduction ranges between 0.5 and 2 kg CO_2 eq/kg. As shown in section 4.3, in this study the average net environmental benefit of food donation is 1.9 kg CO_2 eq/kg.

This article analyzes environmental burdens and benefits of surplus food redistribution, which is institutionally regulated in substance, but much less in form. The consequence is that the data collected are highly heterogeneous and uncertain, which could be significantly reduced if formal, standardized systems for the recovery of food waste were set up. In this way it would be much easier to optimize redistribution, in particular by taking care of the size of emporiums, consumption, and logistics. Despite the difficulties encountered in the development of the study and net of the inefficiencies of some emporiums, it is evident the importance that the recovery of food waste has in reducing the environmental impacts of food supply chains and at the same time ensuring access to food for people in need. For future development of this research it would be useful to improve the modeling of food products by including more detailed processes on the supply chains under consideration and combining the assessment of environmental sustainability with the analysis of the economic and social benefits of surplus food redistribution.

CRediT authorship contribution statement

Mattia Damiani: Conceptualization, Methodology, Formal analysis, Writing - original draft, Writing - review & editing. **Tiziana Pastorello:** Methodology, Data curation, Writing - original draft. **Anna Carlesso:** Methodology, Data curation. **Stefania Tesser:** Project administration, Resources. **Elena Semenzin:** Conceptualization, Project administration, Supervision, Writing - review & editing.

Declaration of competing interest

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

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Appendix A. Supplementary data

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