


Article

Sustainability Assessment of Food-Waste-Reduction Measures by Converting Surplus Food into Processed Food Products for Human Consumption

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Abstract: Food waste is a major challenge for society as it causes economic, environmental and social problems. Many food-waste-reduction measures aim to prevent food waste at the source or by redistributing surplus food via donation. However, it would also be useful to evaluate surplus-food redistribution, where surplus food can be made available for human consumption by valorization (recycling). This paper evaluates food-waste-reduction measures, where surplus food is converted into processed food products for human consumption, which are then sold in a German retail store. The objective is to assess whether this kind of recycling of surplus food is effective in reducing food waste and how sustainable it is considering the economic, environmental and social impacts. The results of this pilot study show a total reduction of 19 kg of food waste within 17 weeks. Furthermore, all products were economically profitable, with a per product net revenue of sold upcycled products between EUR 0.42 and 0.70. The results of the environmental assessment varied from savings of 1.55 kg of CO₂ equivalents/kg of product to the addition of 1.88 kg of CO₂ equivalents/kg of product in product carbon footprint and the addition of between 0.42 and 0.70 mPt/kg of product in product environmental footprint. The social indicators could only be qualitatively described. The results, therefore, can only recommend this recycling option as an effective and efficient food-waste-reduction measure under optimal conditions. More research is needed to describe different recycling situations and to therefore improve the sustainability of the food supply chain.

Keywords: food waste; surplus food; valorization; measure; sustainability assessment



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1. Introduction

Global food waste is estimated to amount to approximately one-third of the edible parts of food produced for human consumption annually [1]. Accordingly, a total yearly waste of 1.3 billion tons of edible food leads to the emission of 3.3 billion tons of CO₂ equivalents, has a blue water footprint of 250 km³, occupies almost 1.4 billion hectares of land and amounts to a direct economic cost of USD 750 billion based on producer prices [2]. At the same time, about 820 million people were undernourished in 2018, and wasting food means missing opportunities to feed the growing world population [3]. Hence, reducing food waste not only contributes to achieving one of the most important challenges of the world, namely improving global food security, but also helps to make the food-production system more sustainable [2,4,5].

The United Nations (UN) has adopted a specific target as part of their Sustainable Development Goals (SDGs): aiming at halving per capita global food waste at the retail and consumer levels and reducing food losses along the production and supply chains (including post-harvest losses) by 2030 (Target 12.3) [6]. An example of a country having committed to meet Target 12.3 of the UN SDGs is Japan. Its parliament enacted the Act on Promoting Food Loss Reduction (Food Loss Act) (Act No. 19 of 2019) in 2019 to take measures to reduce household food waste. However, already in 2001, the Japanese government implemented the Food Recycling Act (Act No. 116 of 2000, amended by Act No 83 of 2007)

to regulate food-waste generation in food-related business and to promote recycling of food waste into feedings, fertilizers or energy if a reduction in food-waste generation cannot be achieved [7]. At the European level, the European Union (EU) and EU countries have also committed to meeting Target 12.3 and reducing food waste as a priority in the EU's Circular Economy Action Plan [8].

As part of work towards this goal, Stenmarck et al. (2016) estimated the volume of food waste in the EU-28 for 2012 to be 88 million tons, including both edible food and inedible parts. Households were the sector contributing the most to food waste (47 million tons or 53 percent) [5]. For Germany, Schmidt et al. (2019) estimated the amount of food waste to be approximately 11.9 million tons in 2015, of which around 6.7 million tons were theoretically avoidable. According to the authors' calculations, the individual contributions of the Food Supply Chain (FSC) stages ranged from 4% for trade to around 52% for private households [9].

To protect the environment and human health by preventing or reducing the adverse impacts from the generation and management of waste, the EU enacted the Waste Framework Directive 2008/98/EC, recommending a waste hierarchy, with preventing waste being the preferred option, followed by preparing for re-use, recycling and other recovery (e.g., energy recovery), and sending waste to landfill should be the last-resort option. With regard to the environmental impact, previous studies analyzed different management options, and the results mostly supported the same waste hierarchy. For example, Brancoli et al. (2020) assessed the relative environmental impacts of different management options for surplus bread and found that a reduction at the source and the use of surplus bread in different valorization pathways (animal feed, donation, beer and ethanol production) are environmentally preferable compared to waste-management options such as anaerobic digestion and incineration [10]. Eriksson and Spangberg (2017) came to the same conclusion based on their investigation on fresh fruit and vegetables [11]. Sulis et al. (2021) showed that their food donation scenarios have the least environmental burden compared to landfilling [12], and Sundin et al. (2022) also found higher carbon emission savings from food donation compared with anaerobic digestion, even when taking rebound effects related to food donation into account [13].

However, only a few of the reviewed studies analyzed the option of recycling within the waste hierarchy, including recovery, by which waste materials are reprocessed into products for human consumption. Furthermore, most studies focused on the environmental impacts, but food waste causes not only environmental problems but also economic and social problems. Hence, all three dimensions of sustainability should be considered when assessing food-waste-management options. To the best of the authors knowledge, only one study exists that assessed a recycling solution based on all three sustainability dimensions. Bergström et al. (2020) assessed surplus food-redistribution units in Sweden with regard to its impact on several sustainability indicators and found that reprocessing surplus food into a processed food product was attributed a high social value due to its effects such as job creation; but at the same time led to financial losses; and compared with other redistribution units, reduced less emissions [14].

This article addresses the abovementioned research gaps by evaluating surplus-food recycling, where the surplus food is still used for human consumption after conversion into processed food products. The objective is to assess whether reprocessing surplus food into processed food products for human consumption is effective in reducing food waste and whether the valorization process is sustainable with regard to the economic, environmental and social dimensions. The overall goal of this evaluation is to contribute to the identification of the most promising food-waste-reduction measures to achieve SDG 12.3 of the UN.

2. Materials and Methods

This case study was set up following a collaboration with the REWE Group, a major food retailer in Germany, and three startups engaged in the field of food-waste re-

duction. The collaboration was set in the context of the German research project “Dialogue Forum on Wholesale and Retail Trade” (For further information about the research project, see https://www.thuenen.de/en/ma/projects/efficient-reduction-of-food-waste-in-wholesale-and-retail-trade/?no_cache=1 (accessed on 20 October 2022)).

2.1. Measure Description and Inventory Data

This article aims to evaluate a food-waste-reduction measure where surplus food or by-products are converted into processed food products that can still be consumed by humans. To sell these upcycled products, a special supermarket shelf (the rescue-shelf) was set up in one store of the retailer. The rescue-shelf, shown in Figure 1, was accompanied by an advertising campaign to draw attention to the upcycled products.



Figure 1. Rescue-shelf in the store with different upcycled products.

The promotion period covered 17 weeks, starting from 4 October 2021 and ending on 31 January 2022. Table 1 gives an overview of the different upcycled products from the three startups placed on the rescue-shelf.

Table 1. Number of items and varieties of the upcycled products placed on the rescue-shelf.

Startup No.	Product Type	Varieties	Number of Items
1	Dumplings	Apple and Cinnamon, Poppy and Almond, Bacon and Onion, Parsley	132
1	Ready-Mix for Bread Balls	Falafel, Pretzel	48
2	Cracker	Mild Peppers, Spicy Pepper	70
3	Edible Disposable Tableware	Drinking Straws, Spoons, Stirrers	80
			Total: 330

All products offered in the rescue-shelf used surplus food or by-products from the different stages of FSC and converted them into processed food products. These processed food products are already approved for the market by the food authorities. Dumplings and ready-mix for bread balls upcycled old bread from bakeries; food items repurposed in crackers included sunflower protein, pumpkin seed flour and apple fiber; and for edible disposable tableware, apple fiber was used. Figure 2 shows the conceptual framework of the process by which the different food items went from being saved by the three startups to being sold on the rescue-shelf via conversion. Furthermore, Figure 2 shows what kind of inventory data are collected from the startups and the store to be used in the sustainability assessment.

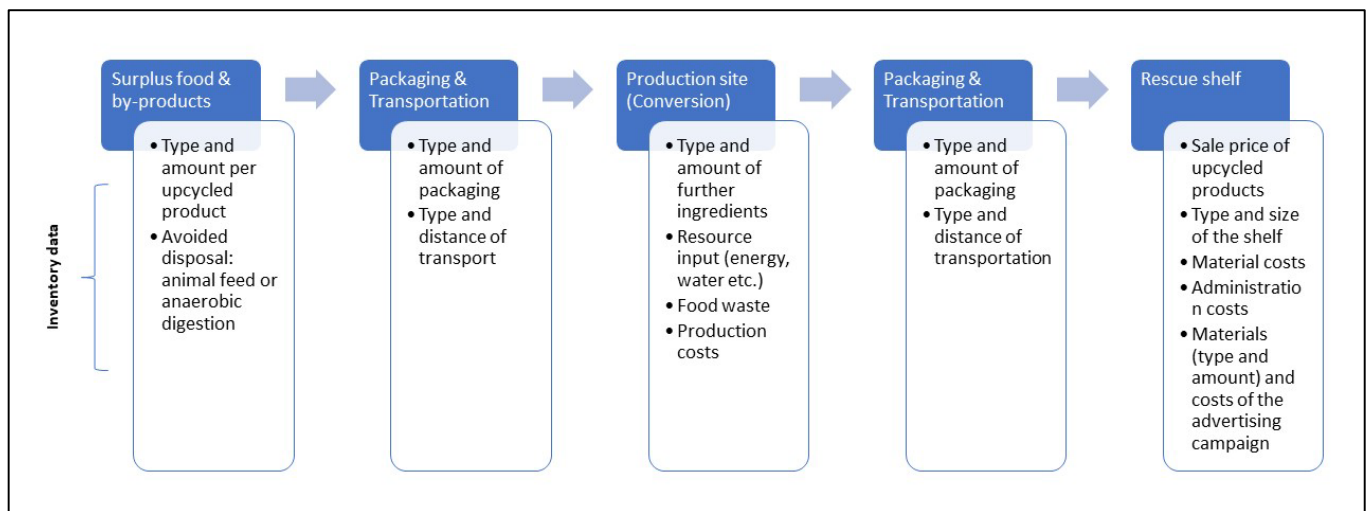


Figure 2. Conceptual framework of the food-waste-reduction measure. Source: Own representation.

2.2. Sustainability Assessment

The evaluation of the food-waste-prevention measure described in Section 2.1 follows the methodology proposed by the Joint Research Centre (JRC) of the European Commission [15] and outlined in Goossens et al. (2019) and Laurentiis et al. (2020) [16,17]. Here, the food-waste-prevention measure is evaluated based on its effectiveness (food-waste-reduction potential) and its sustainability across the environmental, the economic and the social dimensions [18].

Food waste is hereby understood as “any food, and inedible parts of food, removed from the supply chain to be recovered or disposed” [19]. Recovered food includes surplus food removed from any stage of the supply chain and by-products from processing.

The sustainability assessment includes the calculation of the economic, environmental and social changes associated with the conversion of surplus food into processed food products and is carried out by comparing the food chain situation before and after the surplus food was saved by the three startups. Figure 3 illustrates the system boundaries for the two defined scenarios. In the baseline (scenario 1), produced food is sold at the retail level, and surplus food and by-products from FSC are transported to a disposal site (anaerobic digestion or incineration) or used for purposes other than human consumption (e.g., animal feed). After the implementation of the measure (scenario 2), the upcycled products from the startups containing the saved food were offered on the rescue-shelf. The scenario comprises valorization, in which the saved surplus food or by-products are converted into processed food products. This valorization process includes the transportation of saved food from the supplier to the production site, all resources needed to produce the upcycled product (e.g., further ingredients, energy and water use, working hours, packaging and administration efforts), transportation from the producer to the rescue-shelf, and the resources needed to place the upcycled products on the rescue-shelf at the retail level (e.g., materials and administration efforts related to the rescue-shelf). Furthermore, this scenario includes a

system expansion (cf. [11,14]) by considering the effect that the upcycled products might have on substitute goods sold in the same store. It is assumed that the respective upcycled product directly competes with other brands of comparable products and, in the long term, will replace the substitute good and the related costs and impacts of its production.

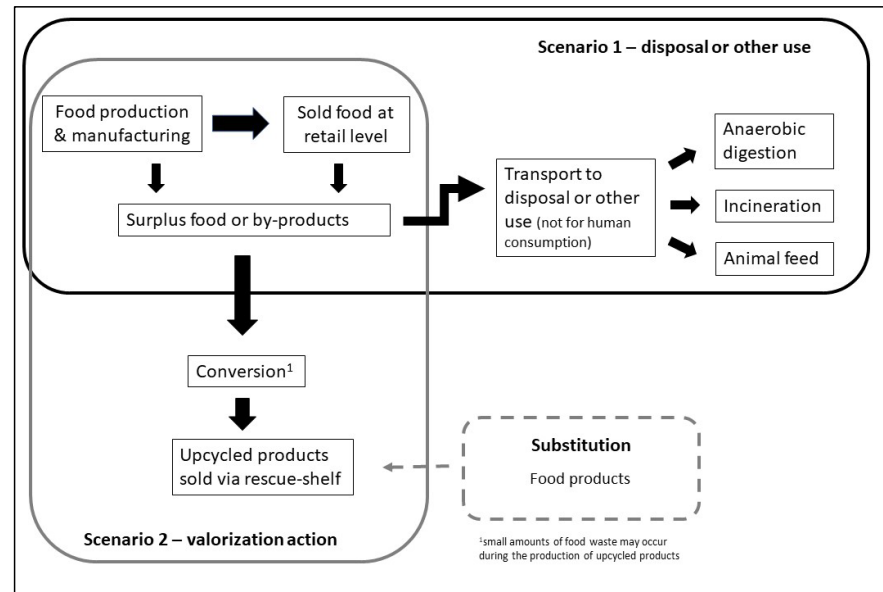


Figure 3. System boundaries for the two scenarios and the substituted food or products in the system expansion. Source: Own representation based on Bergström et al. (2020) and Damiani et al. (2021) [14,20].

2.2.1. Effectiveness of Food-Waste-Reduction Measures

In this case, study, the food-waste-reduction potential is calculated as the amount of saved food (surplus food and by-products) which otherwise would be discarded at any stage of FSC or used for purposes other than human consumption. After the promotional period of the rescue-shelf, the amount of food saved per product was multiplied by the number of respective items sold, leading to the total amount of food saved during product placement.

2.2.2. Environmental Assessment

For the environmental assessment, a life cycle assessment (LCA) approach was used to calculate environmental impacts or savings arising by switching from scenario 1 to 2 (cf. [16]). The following three elements were considered:

A_{en} = Avoided embodied impacts of substituted products;

B_{en} = Net avoided impact of food-waste disposal;

C_{en} = Impacts caused by the implementation of the action.

For valorization, where food waste is avoided by converting surplus food or by-products into processed food products, the embodied impacts of surplus food or by-products are not avoided, but it could be assumed that the upcycled product will replace a substitute good in the long term, leading to the avoidance of embodied impacts related to the ones they replaced [15]. The calculation of A_{en} in scenario 1 is based on the types and amounts of food items replaced at the retail stage (cf. [17]). For food products, the French LCA database Agribalyse 3.0 was used to calculate the avoided embodied impacts of the substituted product [21,22]. As the upcycled products placed on the rescue-shelf are quite special, the most suitable food product was chosen as the substitute. For edible disposable tableware, environmental impacts related to plastic and paper straws were calculated according to Zanghelini et al. (2020) and the LCA database Ecoinvent [23,24]. For spoons and stirrers, the respective environmental impacts for straws were considered using a weighting factor based on their different weights. Based on the waste-treatment options mentioned by each respective startup, the net avoided impacts of food-waste disposal

(B_{en}) were calculated as the difference between impacts avoided by using surplus food and by-products instead of discarding them and the impacts of the disposal of food waste occurring during the production of the upcycled product. The environmental impacts of waste-treatment options were taken from Laurentiis et al. (2020) [17]. If the surplus food or by-products were used for animal feed, we assumed B_{en} as zero. The environmental impacts caused by the implementation of the valorization (C_{en}) comprises the embodied impacts of further ingredients and resource inputs needed for the production of the upcycled product (C_{en1}), additional required transportation (C_{en2}), and packaging (C_{en3}), as well as environmental impacts related to the implementation of the rescue-shelf itself (C_{en4}) (material used for the shelf and advertising). Due to secrecy regarding their recipes, not all startups provided data for all ingredients used, but for the calculation of the embodied impacts of further ingredients, at least 90% of the product mass was covered. Furthermore, the startups were not able to provide data with regard to the resource inputs for production (e.g., energy input for cooking), and thus, this information was estimated based on the literature values and LCA databases. The databases Agribalyse 3.0 and Ecoinvent were also used for the calculation of C_{en} . For the environmental impacts, two indicators were used. First, using the product carbon footprint (PCF), the environmental impacts were expressed as kg of CO₂ equivalents. Second, the product environmental footprint (PEF), which is expressed in millipoints (mPt), was used as an aggregated key performance indicator [25–28]. The functional unit (FU) for the environmental dimension is one kg of product.

2.2.3. Economic Assessment

For the economic assessment, the following two elements were considered to calculate the change in costs by switching from scenario 1 to 2:

A_{ec} = Net revenue of sold products;

C_{ec} = Cost or savings caused by the implementation of the action.

The implementation of valorization leads to a net revenue (sale price less minus purchasing price) from selling the upcycled products, A_{ec} . When the sale price of the startup (purchasing price for the store) was not provided, the net revenue was calculated based on the respective sale price from the rescue-shelf and by assuming a gross profit margin of 32.8%, according to the German Statistical Database [29]. In contrast to the environmental assessment, disposal costs that were avoided were not considered in the economic assessment of the measure because associated savings were made during the upstream stages and, thus, are already included in the sale price of the startups. The cost of implementing the valorization (C_{en}) includes various costs. The substitution of a comparable product results in a net revenue loss of the replaced product, as it is no longer sold (C_{ec1}). As the substituted product is theoretically derived (based on system expansion), its price and the net revenue from product sales have to be assumed. The best suitable product typically available in German retail stores was chosen as the substitute using established branded products. For disposable tableware, only substitutes made from paper were used because the production of disposable tableware made from plastic has been forbidden in the EU since 2021. Furthermore, costs from the rescue-shelf itself (material costs and administration) (C_{ec2}) and for the accompanying advertising campaign (C_{ec3}) were considered. For the economic assessment, changes in costs are expressed in Euro and one item is used as the FU. To analyze the economic performance of the upcycled products, the respective costs were gradually subtracted from A_{ec} in the economic assessment (Section 3.2).

2.2.4. Social Assessment

For the social assessment, we analyze how the rescue-shelf and related sales of upcycled products affect the awareness of the staff and consumers, as well as its effects on jobs along the food supply chain.

3. Results

3.1. Effectiveness of the Rescue-Shelf

The effectiveness of the rescue-shelf, defined as the amount of food saved from becoming waste due to the products sold during the project duration, amounted to 18.8 kg (see Table 2). Selling dumplings resulted in the highest food savings because, first, dumplings make up the largest share of all items sold (68 of 168 items or 40%), with more sales leading to higher savings, and second, the proportion of saved ingredients to all ingredients is quite high for dumplings (60–68%) compared with other products (e.g., 30% for crackers). Only bread balls, with over 90%, have a higher proportion of saved ingredients. Considering that dumplings have the highest product weight compared with all other products (e.g., a glass of dumplings weighs 350 g, while a packet of crackers weighs 40 g), its high proportion of saved ingredients and highest product weight lead to the highest savings.

Table 2. Effectiveness of the rescue-shelf measured in amount of food saved from becoming waste due to the sale of upcycled products by participating startups.

Startup Products	Number of Sold Items	Food Saved (kg)
All products	168	18.80
Dumplings	68	
Apple and Cinnamon	18	3.78
Poppy and Almond	10	2.17
Bacon and Onion	21	5.00
Parsley	19	4.46
Ready-Mix for Bread balls	16	
Falafel	11	1.72
Pretzel	5	0.79
Cracker	49	
Mild peppers	28	0.34
Spicy pepper	21	0.26
Disposable Tableware ¹	35	
Straws	26	
Spoons	7	
Stirrers	2	

¹ Due to secrecy regarding the recipe, the amount of food saved for disposable tableware is not shown here. Source: Author's calculation.

3.2. Economic Assessment of the Rescue-Shelf

Table 3 shows the economic assessment of implementing the rescue-shelf. Costs and savings are calculated in EUR per item in the shelf (not per item sold so that the fixed costs of the rescue-shelf are distributed proportionately) and shown for each product type produced by the three startups.

Table 3. Costs and savings of the economic assessment of the rescue-shelf implementation in EUR per item.

	Dumplings	Bread Balls	Cracker	Straws	Spoons	Stirrers
A_{ec}	1.26	1.20	0.70	0.98	1.07	1.07
C_{ec1}	0.80	0.56	0.17	0.49	0.65	0.37
$A_{ec} - C_{ec1}$	0.46	0.64	0.53	0.49	0.42	0.70
C_{ec2}	3.12	3.12	3.12	3.12	3.12	3.12
C_{ec3}	17.23	17.23	17.23	17.23	17.23	17.23
$A_{ec} - C_{ec1} - C_{ec2} - C_{ec3}$	−19.89	−19.71	−19.82	−19.86	−19.93	−19.65

A_{ec} = Net revenue of sold upcycled products; C_{ec1} = Net revenue loss of substituted products; C_{ec2} = Costs of rescue-shelf material + working for upsetting it; C_{ec3} = Costs for advertising. Source: Author's calculation.

Following the conceptual framework in Section 2.2.3, the economic assessment considers the net revenue of sold upcycled products (A_{ec}) and the costs caused by the implementation of the rescue-shelf (C_{ec}). C_{ec} includes different costs, indicated by the subscripts

in Table 3. First, C_{ec1} refers to the net revenue loss of the substituted product. Subtracting C_{ec1} from A_{ec} results in per item profits between EUR 0.42 and EUR 0.70. Hence, at the individual product level, selling upcycled products is worthwhile for the store from an economic point of view. However, the implementation of the rescue-shelf led to further costs, which must also be considered when assessing the economic performance of the whole rescue-shelf. Second, C_{ec2} refers to costs of the rescue-shelf itself (material costs and administration). C_{ec2} amounts to EUR 3.12 per item and is 5 to 7 times higher than the per item profit. Third, the implementation of the rescue-shelf was accompanied by an advertising campaign, indicated by C_{ec3} , which amounts to EUR 17.23 per item and is 25 to 42 times higher than the per item profit. Considering all costs of C_{ec} would result in a loss of approximately EUR 20 per item sold during the project duration. However, this calculation ignores the fact that the substituted product is also sold via store shelves and advertised by the store. The respective costs are assumed to be covered by the gross profit margin generated by the sale of the substituted product. Following this argument for the upcycled products on the rescue-shelf, costs represented by C_{ec2} and C_{ec3} are assumed to be covered by the gross profit margin of the upcycled products generated not only during the project duration but also during the long-term sale of the upcycled products. As A_{ec} remains positive even if C_{ec1} is subtracted, the upcycled products can overcompensate for the costs of the rescue-shelf and advertising in the long term.

3.3. Environmental Assessment of the Rescue-Shelf

Figures 4 and 5 show the results of the environmental assessment for implementing the rescue-shelf as a product carbon footprint (PCF expressed in CO₂ equivalents) and as a product environmental footprint (PEF expressed in mPt). The environmental impacts caused by the rescue-shelf itself and the advertising campaign (C_{en4}) are not included due to the same arguments made for the economic assessment. The rescue-shelf itself added 0.04 kg of CO₂ equivalents or 0.01 mPt to the environmental impact and the advertising campaign added another 12.4 kg of CO₂ equivalents or 31.5 mPt per item on the shelf, which together results in a strong negative impact on the environment. However, these respective impacts on the environment should not be allocated on the upcycled products offered during the short project duration but must be seen as efforts needed to introduce new products to a store, which will then be sold for a longer period. The environmental impacts and savings were calculated per kg of product and are shown for each variety of each product type from the three startups. Following the conceptual framework in Section 2.2.2, the environmental assessment considers the embodied impacts that were avoided by the substituted products (A_{en}), the net avoided impact of food-waste disposal (B_{en}) and the impacts caused by the implementation of the rescue-shelf (C_{en}). C_{en} includes the different impacts, which are shown separately. As A_{en} and B_{en} refer to environmental savings gained from selling the upcycled product, these impacts are displayed as negative bars; in contrast, C_{en} is presented as positive bars as it refers to the additional impacts caused by production (C_{en1}), transportation (C_{en2}), and packaging (C_{en3}) related to the valorization. Balancing the negative and positive bars for each variety of the products results in the net impact, which indicates whether additional impacts are generated (net impact above the abscissa axis) or impacts are reduced by the measure (net impact below the abscissa axis). The first four bars in Figure 4 show the PCFs of the varieties of dumplings. Additional greenhouse gas emissions caused by the valorization are more than compensated by the greenhouse gas emission savings due to the embodied impacts avoided by the substituted product and the disposal impacts avoided for all varieties. The savings range between 0.74 and 1.55 kg of CO₂ equivalents per kg of product. Differences between the varieties result from the different embodied environmental impacts from the other ingredients needed during production as all other positions are the same for all varieties of dumplings. For example, embodied environmental impacts are higher for animal-based ingredients such as bacon compared to plant-based ingredients such as apples. For the two varieties of bread balls (falafel and pretzel), balancing the negative and positive bars also leads to savings in the

greenhouse gas emissions: 0.58 kg of CO₂ equivalents per kg of product. In contrast, the net impacts of the two varieties of crackers (mild peppers and spicy pepper) are close to zero (0.03 and -0.003 kg of CO₂ equivalents, respectively). For disposable tableware, the sale of all three product types releases additional 1.07, 1.38 and 1.88 kg of CO₂ equivalents per kg of spoons, straws or stirrers, respectively, compared with their plastic counterparts. When compared with those made from paper, the net impacts amount to 1.25, 1.43 and 1.86 kg of CO₂ equivalents per kg of straws, spoons or stirrers, respectively (not shown in Figure 4). The three product types are not directly comparable due to their different packaging sizes and weights.

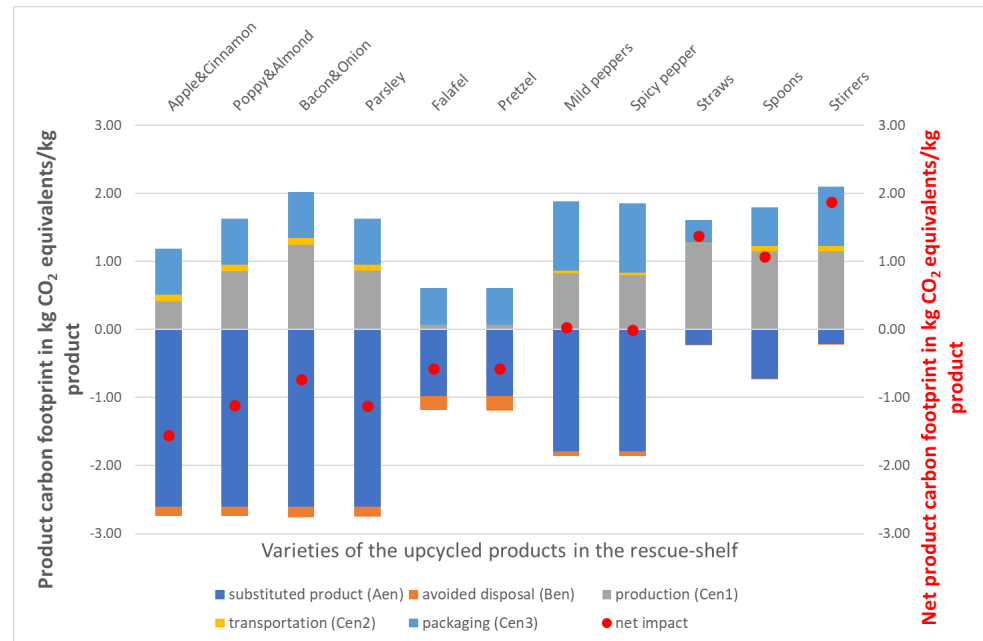


Figure 4. Product carbon footprint of the upcycled products placed on the rescue-shelf, with the varieties individually shown. Source: Author’s representation.

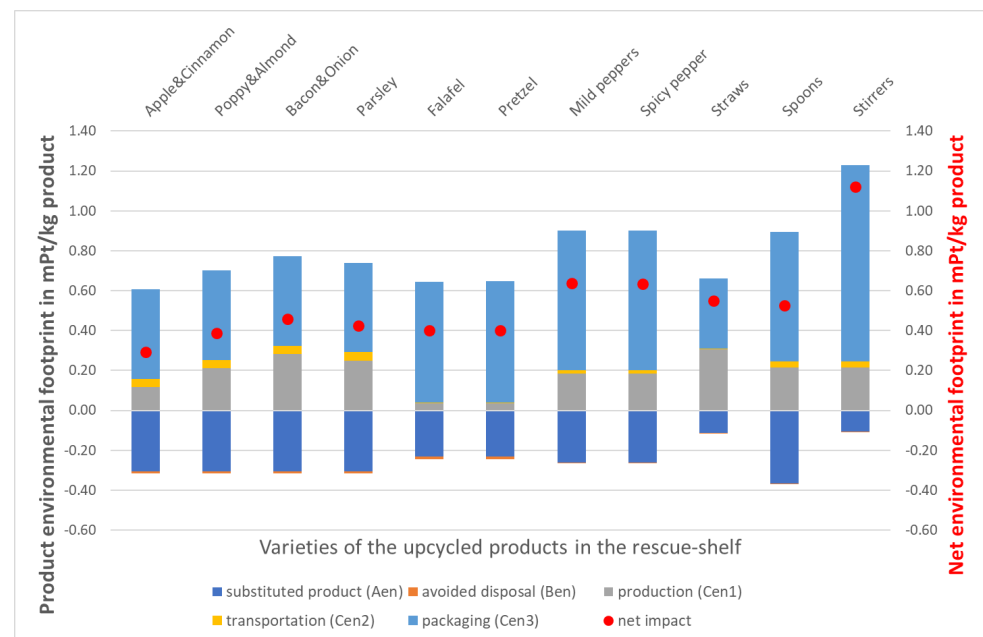


Figure 5. Product environmental footprint of the upcycled products placed on the rescue-shelf, with the varieties individually shown. Source: Author’s representation.

First, the results for the PEF in Figure 5 differ from those for the PCF in Figure 4 in that, for all products, the additional environmental impacts from the measure are not compensated for by the savings. Hence, from the perspective of the PEF, the sale of upcycled products results in further environmental impacts. Figures 4 and 5 show that the impacts of packaging carry more weight in the PEF calculation, while at the same time, the savings of the substituted product are relatively smaller. Second, in the PEF calculation, there is no clear indication of which product type has the lowest additional net impact. The lowest net impacts are associated with dumplings, bread balls, spoons and straws (0.29–0.55 mPt/kg of product), followed by crackers, with 0.63 mPt/kg of product. Stirrers have the highest additional net impact (1.12 mPt/kg of product).

For the environmental assessment, the products on the rescue-shelf can also be compared using the functional unit of one kg of food saved from becoming waste or used for purposes other than human consumption (see Table A1 in the Appendix A for the details). For example, the variety Apple and Cinnamon contains 210 g of bread saved from becoming waste. To save one kg of bread, 4.76 articles have to be sold, resulting in savings of 2.59 kg of CO₂ equivalents but leads to additional 0.49 mPt. The results obtained using the functional unit of one kg of food saved from becoming waste show the trend as that in Figure 4, with dumplings showing the highest savings in terms of greenhouse gas emissions, while disposable tableware leads to increases in emissions. The trend of the total impact according to the PEF differs from that in Figure 5. Using one kg of food saved from becoming waste as a functional unit, bread balls caused the lowest amount of additional millipoints, followed by dumplings, crackers and disposable tableware, which is a result of the high share of food saved and used as ingredients in the bread balls and dumplings compared with that in the crackers and disposable tableware.

3.4. Social Assessment of the Rescue-Shelf

Due to a lack of data, the social effects resulting from the food-waste-reduction measure are only qualitatively described. Each of the three startups whose products were sold on the rescue-shelf in this study helped create jobs. However, the creation of these jobs cannot be attributed only to the implementation of this rescue-shelf, as this method of distributing products is only a small portion of the total sales. However, at least, as the implementation of the rescue-shelf was accompanied by an advertising campaign carried out by the store, the measure may have increased the level of awareness of upcycled products in the customers buying them and, thus, at least may have helped to maintain those created jobs. The staff at the store were also asked whether they were made aware of the topic of food waste due to the introduction of the rescue-shelf. They reported that they are already aware of topics related to sustainability as the store where the rescue-shelf was implemented is a special sustainability-focused store that the retailer uses for testing several similar projects. What will happen to unsold products after the project period was also asked. The upcycled products not sold during the campaign will firstly be further offered on the regular shelves in the store. When the best-before date nears, unsold upcycled products will then be donated to food charities as part of the regular process of the store. At the time of publication, no information was available on how many products were donated, and thus, no quantitative assessment could be made for this social indicator.

4. Discussion

This paper evaluates the conversion of surplus food into processed food products for human consumption as a food-waste-reduction measure with regard to its effectiveness and the associated sustainability. The results show that the rescue-shelf effectively reduces food waste (18.8 kg during the project period), that selling upcycled products is worthwhile for the store from an economic point of view and that the upcycled products on the rescue-shelf show significant variance in the environmental performance. Unfortunately, the social indicators could not be quantified.

In contrast to many studies [10,12,13], the results of this article cannot fully agree with the prioritization of food-waste-reduction measures as dictated by the waste hierarchy. While some products positively affect the environment by reducing greenhouse gas emissions or at least not releasing additional greenhouse gas emissions compared with current waste-management measure (use as animal feed or anaerobic digestion), the disposable tableware had a negative environmental impact, meaning that additional emissions are caused by the sale of the product. However, greenhouse gas emissions are only one of the many categories of assessed impacts. With regard to disposable tableware made from food, the main objective is to reduce the amount of plastic circulating in the economy and to prevent plastic pollution in the environment. This is not considered either in the PCF or the PEF but could lead to completely different results when comparing food-waste-reduction measures, in general, and different upcycled products in particular from the perspective of other environmental impact categories.

Rebound effects were assessed as being negligible for both the upstream and downstream stages of the food supply chain. For the upstream stages, the production quantities were too small to affect other food producers. Instead, upcycled products should be seen as an extension of the product range at the retail level. For consumers (downstream stage), Sundin et al. (2022) found a substantial rebound effect associated with re-spending substitution-related monetary savings due to food donation, offsetting 51% of the potential carbon-emissions savings [13]. As upcycled products are usually more expensive than their alternatives, the respective negative effects should not be observed. However, it cannot be estimated whether there will be rebound effects in the long-term if upcycled products achieve a higher market share.

However, only 51% of the available upcycled products were sold during the project duration. Hence, the food-waste-reduction potential of the rescue-shelf could be up to two times higher if more sales are made. According to CSCP (2022), who conducted a non-representative point-of-sale survey, the rescue-shelf and related advertising were not noticed by the majority of customers, which might explain the low sales [30]. Regarding the sale of these products, the staff at the store mentioned the higher price of the upcycled products in a discount store as a problem as well as the challenge of trying to convey the message behind some of the products to the costumers (e.g., when by-products such as apple fiber are used in an upcycled product, as a lot of explanation about why these products help reduce food waste is needed). Hence, the type of rescue product and the type of saved food seem to be crucial for a successful sale. Due to lower-than-expected sales, the viability of the measure has to be assessed as low and it is not recommended as an effective and efficient food-waste-reduction measure to other companies in the sector if implemented in the same way. However, much can be learned from this experience to improve the effectivity and efficiency of the rescue-shelf: First, do not place the products on a special shelf but, rather, near their alternatives. Customers who are looking to purchase a salty snack will choose from the variety of chip products offered at the store and may choose the upcycled one. Second, the economic and environmental assessments indicated that advertising caused high costs and environmental impacts. Even if respective advertising campaigns are carried out in order to make the products known and to improve the image of the company, it is recommended to keep advertising costs and impacts low to achieve a good economic and environmental performance. Since the measure is easily transferable, other retailers could test the placement of upcycled products by considering the points mentioned.

For both the economic and environmental assessments, the selection of suitable substitutes is a limitation of this study as it is associated with a high degree of uncertainty. A reduction in sales of other established products in the store could not be detected due to the relatively short test period, which would be an indicator of whether substitution processes would take place. Research on these mid- or long-term substitutions would be very valuable in making respective environmental assessments more reliable and in including related rebound effects induced in the supply chains of the products being replaced. Eriksson and Spangberg (2017) also noted that their assumptions about the alternative

products as being the weakest point in their valorization scenario because many different substitutes can be considered, each with different environmental impacts [11]. However, in accordance with Caldeira et al. (2019), it is reasonable to assume that such a phenomenon takes place in the long term and the best available product was chosen to calculate the substitution process in the economic and environmental assessments [15]. Nevertheless, the estimated net revenue loss and the environmental credits of the alternative strongly impact the overall outcomes, and thus, the results should be interpreted with caution.

5. Conclusions

The objective of this paper was to assess whether reprocessing surplus food into processed food products for human consumption is an effective food-waste-reduction measure and how this recycling option affects the sustainability of the food supply chain across the economic, environmental and social dimensions. The results of the evaluation are valuable in this area of research because most studies dealing with food-waste-reduction measures have only evaluated actions aimed at preventing food waste at the source or by redistributing via donation, but so far, little is known about surplus-food redistribution by valorization.

Overall, the rescue-shelf effectively reduces food waste, but as only half of the upcycled products were sold during the project duration, the total food-waste-reduction potential could not be realized. Furthermore, only the economic assessment shows unreservedly positive results for the upcycled products, while the environmental assessment reveals significant variance in the environmental performance. Accordingly, depending on the product type, there can be both savings and additional environmental impacts. The social assessment did not achieve sufficiently robust results to be used as an assessment of this food-waste-reduction measure. The results therefore cannot fully recommend this recycling option as an effective and efficient food-waste-reduction measure to other companies in the sector if implemented in the same way.

Accordingly, this article indicates a need for further research. In particular, testing the implementation of the rescue-shelf in other stores with different customer groups to find out what kind of product placement and which customer characteristics positively influence the success of selling upcycled products is recommended. Furthermore, the cost and impacts of advertising should be kept as low as possible. In general, evaluating the further valorization of surplus food to learn more about their usefulness in improving sustainability across the environmental, economic and social dimensions is recommended.

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Appendix A

Table A1. Total impact from saving 1 kg of food with the sale of the products on the rescue-shelf.

	Amount of Saved Food per Product (g)	Factor	Total Impact (kg of CO ₂ Equivalents/kg of Saved Food)	Total Impact (mPt/kg of Saved Food)
Dumplings				
Apple and Cinnamon	210	4.76	−2.59	0.49
Poppy and Almond	217	4.61	−1.80	0.63
Bacon and Onion	238	4.20	−1.08	0.67
Parsley	235	4.26	−1.67	0.63
Bread Balls				
Falafel	156	6.39	−0.63	0.44
Pretzel	158	6.33	−0.62	0.43
Crackers				
Mild peppers	12.0	83.3	0.11	2.12
Spicy pepper	12.4	80.7	−0.01	2.05
Disposable tableware ¹				
Straws			27.6	11.0
Spoons			17.8	8.79
Stirrers			31.3	18.7

¹ Due to secrecy regarding the recipe, the amount of food saved per product and the resulting factor for disposable tableware are not shown here.

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