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What to Do with Food Waste? A Holistic Feasibility Framework to Evaluate Different Solutions

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Abstract: Food waste is generated at several stages of the food chain. According to the European Waste Hierarchy, the creation of food waste should above all be prevented, meaning that waste materials with good microbial and nutritional quality should be directed to food use, either directly or through light processing. However, to be feasible, food waste utilisation solutions should be economically profitable, environmentally sustainable and scalable to provide a means to utilise a larger share of the raw materials. In this study, we propose a feasibility evaluation approach for food waste utilisation and prevention solutions. We use two case examples: (1) an artisan bar soap product based on carrot peels, and (2) the retail selling of 2nd class carrots. Both cases are evaluated with six feasibility indicators: edible food waste reduction potential, scalability, level at waste hierarchy, climate impact reduction potential, economic impact, and social impact. Case 2 performed better regarding all indicators other than economic impact. Critical aspects that need to be improved included climate reduction potential for both cases and food waste reduction potential for case 1. The results show that this kind of a holistic approach is useful in identifying the most feasible food waste prevention and utilisation measures.

Keywords: food waste; side flow; sustainability; resource efficiency; vegetables

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1. Introduction

The United Nations and the European Commission have set a target to reduce consumer and retail food waste by half and minimise overall food waste in the food chain by 2030 [1,2]. Hence, there is a high political pressure to reduce food waste and find better utilisation for side streams. Food waste is generated during food production and consumption [3,4]. On farms, part of the yield does not enter the next step in the food chain due to several reasons, e.g., quality defects, overproduction or lack of suitable marketing channels [5]. According to the European Waste Hierarchy [6], the creation of waste should above all be prevented, meaning that food waste materials with good microbial and nutritional quality should be directed to food use, either directly or through light processing. This can be conducted, for instance, by finding new ways to market the products (e.g., farm shops) or processing the materials into new products (e.g., juices, jams). De Brito Nogueira et al. [7] list different possibilities to use fruit and vegetable waste biomass. These include the direct recovery of high-value compounds, the production of bioenergy or packaging material, and use as a low-cost culture medium in biotechnological processes.

However, while the scientific literature identifies several solutions to reduce or utilise food waste [8–12], most of the studies fail to evaluate the scalability and food waste prevention potential of the suggested solutions. Additionally, since the target of food waste reduction is also to reduce the overall environmental impact of food production systems and preferably be economically sound, there is also call for indicators to evaluate the overall sustainability of the suggested actions [13]. There are several studies on creating sustainability evaluation frameworks for eco-innovations. For instance, the European Commission has established Circular Economy Indicators for its member countries to compare the performance of each country [14]. Moreover, Geng et al. [15] and Hansen et al. [16] suggest more complex frameworks to rate sustainability innovations, including ecological, social and economic aspects of sustainability.

Different kinds of decision-making models have been developed to assess the sustainability of solid waste management. Morrissey and Browne [17] identified three different types of decision-making models used in municipal solid waste management: models based on cost–benefit analysis, models based on LCA (Life Cycle Assessment), and models based on the use of multi-criteria decision-making (MCDM). Models using cost–benefit analysis consider economic aspects, while models based on life cycle analysis are based on the assessment of environmental impacts of all phases of a production chain that lead to the creation of waste. Models based on MCDM, on the other hand, consider both economic and environmental criteria in combination with social aspects. They typically include a large set of indicators and the assessment is based on ranking several different alternatives (of, for example, waste management options). For example, Milutinovic et al. [18] developed an MCDM method for the sustainability assessment of different municipal waste management options. The indicators included environmental (greenhouse gas, acid gases, NOx, VOC and heavy metal emissions, energy consumption, waste volume reduction, recycling rate), economic (investment costs, operational costs, fuel cost, revenues) and social indicators (job creation, public acceptance). Moreover, Iacovidou and Voulvoulis [19] developed a screening and decision support framework to assess and compare the sustainability performance of municipal food waste management options based on MCDM. The framework includes economic, environmental and social criteria. The environmental criteria used were energy resource consumption, non-energy resource consumption, renewable energy generation, greenhouse gas emissions, eutrophication potential, land use, chemical fertilisers/peat substitution, and human toxicity potential. The economic criteria included operational and maintenance cost, capital cost, utilities cost, taxation, revenue generation and subsidy and incentives. Social criteria included acceptability, job creation, health and safety, implementation and adaptability, noise implications and odour implications.

Mourad [20] suggested to rate food waste reduction solutions based on waste hierarchy [6], where food waste prevention is the most desirable solution. Furthermore, Mourad suggests dividing food waste prevention strategies between optimisation strategies, which Mourad labels as ‘weak prevention stategies’, and structural change strategies (thus, ‘strong prevention stategies’). Mattsson et al. [21] studied the economic cost and climate impact associated with the retail waste of fruit and vegetables. Moreover, De Menna et al. [22] presented a framework for the LCA and life cycle costing of food waste prevention and valorisation solutions, taking into account environmental and economic aspects. Goossens et al. [23] reviewed the existing food waste prevention measures and the methodologies applied for evaluating their economic, environmental and social performance. They found that the environmental performance was evaluated for 65%, economic performance for 77% and social performance only for 9% of the reported measures. The European Commission Joint Research centre has developed a more comprehensive evaluation framework for food waste prevention actions [24]. The framework includes six criteria: quality of the action design, effectiveness, efficiency, sustainability of the action over time, transferability and scalability and intersectorial cooperation.

Based on the above-mentioned existing literature on innovation sustainability frameworks, food waste management and reduction sustainability frameworks, the consensus is that an optimal feasibility framework should consider both overall sustainability (including economic, environmental and social aspects) as well as waste hierarchy level and scalability of the different food waste utilization solutions. We also found out that while the existing literature provides a good basis to evaluate different food waste prevention and utilisation solutions, they often lack specificity and/or are too complex. Therefore, in this paper we propose a feasibility framework specified for the utilization solutions of agricultural food waste that would be specific and simple enough to be used especially in the early design stage where the main aim is to screen through the most promising solutions. Our aim was to provide a simple enough tool for a wide range of food chain actors also without expert knowledge in MCDM. The suggested feasibility indicators include (1) edible food waste reduction potential, (2) scalability, (3) level at waste hierarchy, (4) climate impact reduction potential, (5) economic impact, and (6) social impact. To demonstrate the feasibility assessment, we use data collected as part of the project Arvo-Bio (Puutarhatuotannon uusi kiertotalous—The new circular economy of horticultural production (2015–2019); https://www.hamk.fi/projektit/arvobio-puutarhatuotannon-uusi-kiertotalous/#perustiedot, accessed on 1 September 2022), in which novel solutions for utilising horticultural by-products were studied. From the project case examples, we selected two case examples representing ways to utlise side flow originating from the production of carrot, which is one of the most important horticultural crops in Finland. The case example 'an artisan bar soap' uses carrot peels as a key ingredient and represents a non-food high-value product (case example 1). The second case is 'retail store selling of 2nd class carrots', where the pricing is lower but the carrot ends up as food (case example 2).

2. Materials and Methods

2.1. Food Waste Reduction Framework

The performance of the solutions for each suggested feasibility indicator are classified according to four levels from most desirable to not desirable (Table 1). The classification levels are described in Table 2. More detailed descriptions on the assessment of the different indicators are given in Sections 2.2–2.7.

Table 1. Feasibility framework. Colour codes indicate the differences compared to the situation where the side flow is not utilised: desirable (+, light green), indifferent (0, yellow), not desirable (-, orange). The overall food waste solution scores calculated as the average of the individual indicators.

Side Flow Utilisation Solution	Edible Food Waste Reduction Potential	Scalability	Level at the Waste Hierarchy	Climate Impact Reduction Potential	Economic Impact	Social Impact	Food Waste Solution-Score
Example 1	+	+	0	0	-	-	0

Table 2. The classification for the performance of the food waste utilisation solutions. Colour codes indicate the differences compared to the situation where the side flow is not uti-lised: most desirable (++, dark green), desirable (+, light green), indifferent (0, yellow), not desirable (-, orange).

Feasibility Indicator	Classification Criteria	Most Desirable (++)	Desirable (+)	Indifferent (0)	Not Desirable (-)
Edible food waste reduction potential	Reduction potential of edible food waste related to the current practice	50–100%	10–50%	1–10%	<1%
Scalability	Utilisation potential of food waste related to the current practice	Highly scalable	Scalable	Weak scalability	Not scalable
Level at the waste hierarchy	End use of food waste	Strong prevention	Weak prevention and Reuse	Recycling and Recovery	Disposal
Climate impact reduction potential	Reduction potential of climate impact related to the current practice	50–100%	10–50%	1–10%	<1%
Economic impact	Increase of profit margin related to the current practice	50–100%	10–50%	1- 10%	<1%
Social impact	Acceptability compared to the current practice	Clearly more acceptable	Somewhat more acceptable	Equally acceptable	Less acceptable

2.2. Edible Food Waste Reduction Potential and Scalability

The potential of the solution to reduce food waste in the production chain was assessed based on whether the side flow material that would be utilised was primarily meant for food use. For example, in agricultural production, straw and vegetable tops are not initially produced for food use and their utilisation should thus not be regarded as a top priority [5]. The scalability of the food waste prevention solutions, i.e., the ability of the activity to grow larger, was assessed by comparing the size of the potential market of the new product to the availability of the raw material that could be utilised (based on total mass in kilograms).

2.3. Level at Waste Hierarchy

The level of the studied solutions at waste hierarchy was assessed by classifying them according to the framework originally proposed by EC [6] and supplemented by Mourad et al. [20] (Figure 1). According to Mourad [20], strong prevention strategies require structural changes in the production system, while weak prevention strategies are described as optimisation of the current practices. 'Reuse' means redirecting food to human consumption, and 'recycling' alternative use, such as using it as a feed ingredient or in industrial processes. 'Recovery' means energy production or land improvement and 'disposal' that the biomass is not further used.

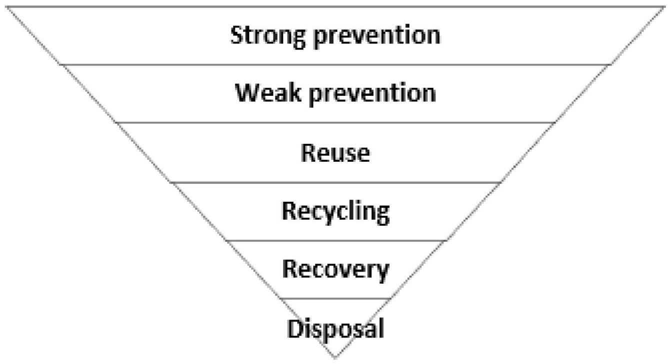

Figure 1. Waste hierarchy levels. Adapted from EC [6] based on Mourad [20].

2.4. Climate Impact Reduction Potential

The climate impacts of the waste utilisation solutions were assessed, taking into account the greenhouse gases CO_2, CH_4 and N_2O and compared to the climate impact of the current practice using attributional Life Cycle Assessment (LCA) methodology (ISO 14040:2006; ISO 14044:2006). The system boundary included all material and energy inputs, including transport. A more detailed description of the climate impact assessment is provided in Appendix A.

2.5. Economic Impact

The economic impact was assessed based on the profit margin of the utilisation solution related to the profit margin of the current practice. For this assessment, we first estimated the expected produce price in euros by identifying the target consumer groups and products that compete in the same product category, taking into account the product-specific aspects that can be used as marketing arguments to increase product value. Then, the cost level of the utilisation solutions was calculated and compared to the expected producer price. A more detailed description of the economic impact assessment is provided in Appendix A.

2.6. Social Impact

Social impacts of the utilisation solutions were assessed based on acceptability, similar to what was conducted in previous studies related to waste management sustainability frameworks [18,19]. Acceptability was estimated qualitatively based on whether comparable solutions already exist commercially and how they are perceived by the consumers, compared to the acceptability of the current practice.

2.7. Carrot as a Case Product

In this study, we chose carrots as a case-product to study and demonstrate the use of food waste. In Finland, the carrot is the most cultivated open-field vegetable [25]. According to a previous study [26], out of all carrot production, 26% is not directed to the food chain (SD 0.15, $n = 27$ farmers). Most of this rejected carrot mass occurs after harvest during sorting (55%) or storing (28%), while 13% occurs during harvest (and is left either unharvested or unsorted). There is, however, great variation from 0 to 59% between farmers. The most important reasons for rejections are wrong-sized or shaped carrots or other cosmetic faults (48%), and plant diseases, including storage diseases (24%). The rejected carrots are mainly used as animal feed (42%) or composted (30%). Carrots with cosmetic faults typically end up as animal feed.

Second-class carrots can be further processed to new food products by, e.g., peeling and processing them to 'baby carrots' [27]. This way the carrot peel mass ends up as side flow, which is typically composted on farm. However, the peel mass can also be used as value-added products, e.g., in cosmetics. Second-class carrots can also potentially be used directly as food because their nutritional and hygienic quality is as good as that of 1st class carrots [28]. However, selling the products as 2nd class is often not profitable for the farmer because the producer price is remarkably lower [29]. Farmers are also afraid that selling cheaper 2nd class products alongside 1st class alternatives may cause unwanted competition and reduce sales of the 1st class product [30].

3. Results

3.1. Scalability and Edible Food Waste Reduction Potential

3.1.1. Artisan Bar Soap

The availability of carrot peels on one Finnish case farm is ca. 2400 kg in a month, which would be enough for producing 50,000 soap bars with the recipe used in our case study. Annually, as many as 600,000 bars could be produced, requiring industrial-level production assembly lines and probably international markets for carrot peel bar soap (since the population of Finland is only about 5.5 million). Therefore, additional solutions would likely be needed to find use for the majority of the carrot peel side flow already from one farm. Considering the Finnish total carrot production and that carrot peeling occurs also in several other companies, it seems extremely unlikely that carrot peel soap could provide a significant solution to the utilisation of the total available carrot peel mass. Moreover, this solution does not reduce edible food waste, because carrot peels are usually removed and not consumed. Potentially, the carrot peel mass is edible, because carrots can be consumed as such or prepared as an ingredient in cooked dishes after washing without removing the peel.

3.1.2. Retail Selling of 2nd Class Carrots

The sales of the 2nd class carrots were 31% of that of the alternative 1st class product (unpacked 1st class carrots) during a two-week-long consumer study in November 2018 [31]. In proportion to the national annual 1st class carrot yield that is sold to food use (calculated as an average of years 2014–2018, [25]) and the estimated 2nd class carrot yield (12% of total carrot production, [26]), at least most of the 2nd class yield could potentially be sold to consumers. However, this could mean that as a rebound the sales of the 1st class product are reduced. On the other hand, if the overall carrot consumption is increased, this could lead to increased production, in which case the amount of food waste would not be reduced after all. Therefore, the result should be considered somewhat uncertain.

3.2. Level at Waste Hierarchy

3.2.1. Artisan Bar Soap

Using carrot peels for soap production represents 'recycling strategy' according to the waste hierarchy definition (Figure 1), as the solution does not prevent the creation of food waste and it is not used as food, but directed to a different use.

3.2.2. Retail Selling of 2nd Class Carrots

Directing 2nd class carrots to food use straight from the farm would introduce a structural change to the operation of the food chain. This is because this kind of product with cosmetic defects are currently not considered acceptable for human use and normally directed for use as animal feed. Thus, the solution requires change in social acceptability and if implemented successfully it would be classified as 'strong prevention strategy', which is the best option according to the waste hierarchy definition (Figure 1).

3.3. Climate Impact Reduction Potential

3.3.1. Artisan Bar Soap

In the bar soap case, the production of the soap increased the climate impact by 5% when compared to a situation where the peels would be composted and an alternative soap product would be used (2.8 vs. 2.7 kg CO_2-eq./kg soap). The majority of the climate impact was caused by the production of the plant oils and the rest of the raw materials and energy use had only a minor impact.

3.3.2. Retail Selling of 2nd Class Carrots

Selling also the 2nd class carrots for human consumption reduced the climate impact by 6% when compared to the current situation, where only 1st class carrots were sold for human consumption and the 2nd class carrots were sold to feed use. The total climate impact was 0.12 kg CO_2-eq./kg for the retail selling of both 1st and 2nd class carrots and 0.13 kg CO_2-eq./kg for the current situation.

3.4. Economic Impact

3.4.1. Artisan Bar Soap

Soap production is relatively inexpensive and does not require complicated equipment, so it can easily be conducted on a small scale. Using carrot peels in soap will not significantly alter the cost of soap production. The sales/profit margin for one 100 g soap piece was calculated to be ca. EUR 5.5, while the selling price for would be 9 EUR/piece (benchmarking with similar products in the market). Therefore, producing artisan soap is significantly more profitable compared to the reference situation in which the carrot peels would be composted and most likely would not result in monetary benefits.

3.4.2. Retail Selling of 2nd Class Carrots

The difference between the production costs and producer price of 1st class carrots for the farmer is very small, less than 1 cent per kg. Considering the lower prices of the 2nd class yield, the profit margin of selling the carrots both for animal feed and for human consumption is negative. However, the producer price of selling for human consumption is still greater compared to animal feed and thus can decrease the losses for the farmer. In addition, if the price difference of the 1st and 2nd class carrots was smaller than the current 50%, the profitability would increase.

3.5. Social Impact

3.5.1. Artisan Bar Soap

Based on the assessment of the economic impact (Section 3.2), several artisan soap products already exist on the market and some even contain carrot as a raw material. If the products are sufficiently labeled to inform the consumer about the ingredients, so that, e.g., people with allergies can avoid the product, there is no reason to assume that there would be any significant problems related to the acceptability of an artisan carrot soap product. However, currently the carrot peels are composted on farm and composting is also a largely accepted practice [32]. As we were not able to carry out an acceptability study comparing composting of carrot peels and their use in soap in this study, we estimate them to be equally acceptable.

3.5.2. Retail Selling of 2nd Class Carrots

Based on the consumer study described in the assessment of the economic impact (Section 3.2), most of the consumers are willing to buy carrots that differ from the 1st class in their size and shape, at least if they are sold with a reduced price. Similar results have also been found in international studies [33,34]. The current practice would be to sell the 2nd class carrots for animal feed, meaning that retail selling would increase the share of the carrot yield used as food. Considering the current food waste reduction goals [1,2], it was assumed that food use of the 2nd class carrots would also be preferred by the consumers at least somewhat more than feed use.

3.6. Framework to Evaluate Food Waste Reduction Solutions

The results of the feasibility analysis are summarised in Table 3. In the bar soap case, the use of carrot peels did not decrease edible food waste or the climate impact of the soap, the scalability was low, and it would also not be a very good solution considering the waste hierarchy. However, due to the characteristics of the carrot soap, it could be marketed as a special product with added value. Therefore, soap production is clearly economically more profitable than composting of the carrot peels (high economic possibility). The acceptability of soap production is estimated to be equally acceptable compared to the current practice.

Table 3. Summary of the feasibility assessment results of the studied side flow utilisation solutions. Colour codes indicate the differences compared to the situation where the side flow is not utilised: most desirable (++, dark green), desirable (+, light green), indifferent (0, yellow), not desirable (-, orange).

Side Flow Utilisation Solution	Edible Food Waste Reduction Potential	Scalability	Level at the Waste Hierarchy	Climate Impact Reduction Potential	Economic Impact	Social Impact	Food Waste Solution-Score
Artisan bar soap	-	0	0	-	++	0	0
Retail selling of 2nd class carrots	++	++	++	0	+	+	++

The case of 2nd class carrots is highly scalable, and it would be possible to get a relatively large amount of edible food waste back into human consumption, meaning that it would be a good solution to reduce food waste. It is also at a high level of the waste hierarchy. On the other hand, the solution does not decrease the climate impact unless we assume that in the current situation, non-valuable uses do not have climate impact. In the latter case, the climate impact would reduce. Additionally, selling the 2nd class products for food use is economically more profitable for the farmer than selling them for feed use. Moreover, it can be assumed to be more acceptable from the consumer's point of view.

4. Discussion

Since there is a high political pressure to reduce food waste and improve the uses of food side flows [1,2,6], tools to evaluate different measures are also needed. In previous literature, it has been shown that several indicators are needed in the sustainability assessment frameworks of different waste management options [18,19] as well as frameworks designed for the assessment of sustainability innovations [13,15,16]. The two case examples in the present study also demonstrate that we need several indicators to highlight different aspects in order to choose the most desirable options and find critical improvement needs. For instance, whilst the cosmetic industry will turn low-value ingredients into high-value products, it can only utilise a low proportion of agricultural side streams. Since the European Commission target is to cut food waste mass in half by 2030, more effective large-scale solutions are required, such as better usage of 2nd class vegetables. Hence, it is probable that scalability is actually the most pressing indicator at the moment.

In this study, we have suggested that edible food waste reduction potential, scalability, level at waste hierarchy, climate impact, economic impact and social impact bring important information of the effectiveness of different options. Besides these indicators, there could be several other indicators, for instance, other environmental impacts such as biodiversity and eutrophication [35,36]. Additionally, other social impacts than acceptability could be evaluated. For example, job creation and health and safety have been used in previous studies assessing the sustainability of waste management options [18,19]. In this study, our aim was to develop a simple-enough tool for a wide range of food chain actors also without expert knowledge in MCDM. However, similar indicators could be used as a part of a more structured MCDM method.

We propose that a similar, more holistic approach would be used in every situation when deciding between different food waste reduction and utilisation measures. Our approach is suitable when deciding whether one should upscale the chosen case studies. In fact, the suggested approach would be suitable already when deciding whether it is even worthwhile to begin the trial. In addition, before the actual feasibility assessment, it is useful to consider the following questions in the planning phase of the side flow reduction and utilisation measures: (1) Are more pre-treatments required for food waste to be suitable for the planned new use compared to a situation where an alternative product is used? Do they require remarkable additional use of energy, water or human labor? (2) Can the new utilisation solution create added value for the new product or significantly decrease the costs related to the current use of food waste? (3) Can the new utilisation solution provide a way to utilise a large amount of the available food waste?

4.1. Artisan Bar Soap

Our results show that the most critical aspects related to the use of carrot peels in the production of an artisan bar soap are the edible food waste reduction potential and climate impact reduction potential (Table 3). The edible food waste reduction potential could be increased by finding other cosmetic products in which the carrot peel mass could be used, utilising its skin-nourishing compounds, such as vitamin A and E [37]. Moreover, commercial use could be found for the fiber mass that comes as a side product from the juicing of the peel mass. Possible alternatives could be used as an ingredient in bakery products or animal feeds and pet foods.

Similar results related to climate impact have been found previously by Secchi et al. [38], who assessed the environmental impacts of replacing synthetic ingredients in a face cream product with natural compounds derived from olive oil industry by-products. Moreover, their results show that the use of new, more natural compounds does not necessarily decrease the environmental impacts, such as the climate impact of the product, because more pre-treatments can be required for the compounds to become suitable for use as cosmetic ingredients. However, with careful design of product formulations and ingredient dosage, the environmental performance could be remarkably improved.

4.2. Retail Selling of 2nd Class Carrots

The most critical aspect related to the retail selling of 2nd class carrots is the climate impact reduction potential (Table 3), which was relatively small compared to the current practice, where only the 1st class carrots are sold to food use. Previously, Ribeiro et al. [39] studied the sustainability of the operation of a non-profit co-op, called Fruta Feia (Ugly Fruit), which commercialises 2nd class fruits and vegetables that Portuguese farmers cannot sell through the conventional marketing channels. The assessment included greenhouse gas emissions associated with the transport and packing of the products as well as estimates of how greenhouse gas emissions were lowered by avoiding the landfilling of the products. The results show that the utilisation of 2nd class products results in an emission reduction of 0.14 kg CO_2-eq/kg compared to the situation where the 2nd class products are deposited to landfill.

5. Conclusions

We proposed a feasibility evaluation framework of food waste prevention and utilisation solutions including six indicators: edible food waste reduction potential, scalability, level at waste hierarchy, climate impact, economic impact, and social impact. The results show that the framework can be used to both assess the overall sustainability and feasibility of food waste reduction and utilisation solutions and help find critical aspects that need to be improved. The framework would be a useful tool in situations when choosing what kind of food waste reduction and utilisation solutions to upscale. Ideally, the feasibility aspects should be considered in the planning phase of the solutions, before any piloting takes place.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A.

Appendix A.1. Calculation Details of Climate Impact Reduction Potential and Economic Impact

Appendix A.1.1. Calculation Details of Climate Impact Reduction Potential

The climate impacts of the waste prevention solutions were assessed using attributional Life Cycle Assessment (LCA), taking into account the greenhouse gases CO_2, CH_4 and N_2O and compared to the climate impact of the current practice. The system boundary included all material and energy inputs, including transport. The system boundaries of the case examples are presented in Figures A1 and A3. The functional units were 1 kg of carrot peel soap (Figure A2) in case example 1 and 1 kg of 2nd class carrots in case example 2.

Appendix A.1.2. Artisan Bar Soap

In case example 1, carrot peels from the processing of 2nd class carrots are utilised. The peel mass is first juiced, and the juice is mixed with the soap stock consisting of plant oils, beeswax, honey and sodium hydroxide (NaOH). The carrot fiber mass that remains after the juicing process can be used as raw material in other food products, such as bakery products.

The inputs needed for the soap production are presented in Table A1.

Table A1. Input need for soap production.

	Consumption/kg Soap	Cost, EUR/kg Soap	Source of Cost Estimate
Input Materials, kg			
Carrot peels	0.476	0.01	
Linseed oil	0.162	3.17	https://www.karkkainen.com/verkkokauppa/pellavansiemenoljy-500-ml, accessed on 13 June 2019
Turnip rape oil	0.599	1.52	https://www.k-ruoka.fi/kauppa/tuote/pirkka-rypsioljy-900ml-6410405191434, accessed on 13 June 2019

Table A1. *Cont.*

	Consumption/kg Soap	Cost, EUR/kg Soap	Source of Cost Estimate
Beeswax	0.049	0.85	https://www.lahtisenvahavalimo.fi/mehilaisvaha-kosmetiikka.html, accessed on 13 June 2019
Honey	0.014	0.15	https://www.mehilaishoitajat.fi/?x118281=5599710, accessed on 13 June 2019
NaOH	0.099	0.52	https://www.lahtisenvahavalimo.fi/saippuatarvikkeet/lipea/lipearae-10--8-kg-toimitus-vain-matkahuollossa.html, accessed on 13 June 2019
Water	4.762	0.01	https://julkaisu.hsy.fi/vesihuollon-hinnasto-ja-palvelumaksuhinnasto-2019.html, accessed on 13 June 2019
Packing material (paper bags from recycled paper), kg	0.002	0.80	https://www.napakka.fi/aromipussi-eko, accessed on 13 June 2019
Electricity, kWh			
Juicing	0.033		
Wax melting	0.048		
Mixing	0.014		
Washing machine	0.476		
Total electricity	0.571	0.08	https://www.sahkonhinta.fi/summariesandgraphs, accessed on 13 June 2019

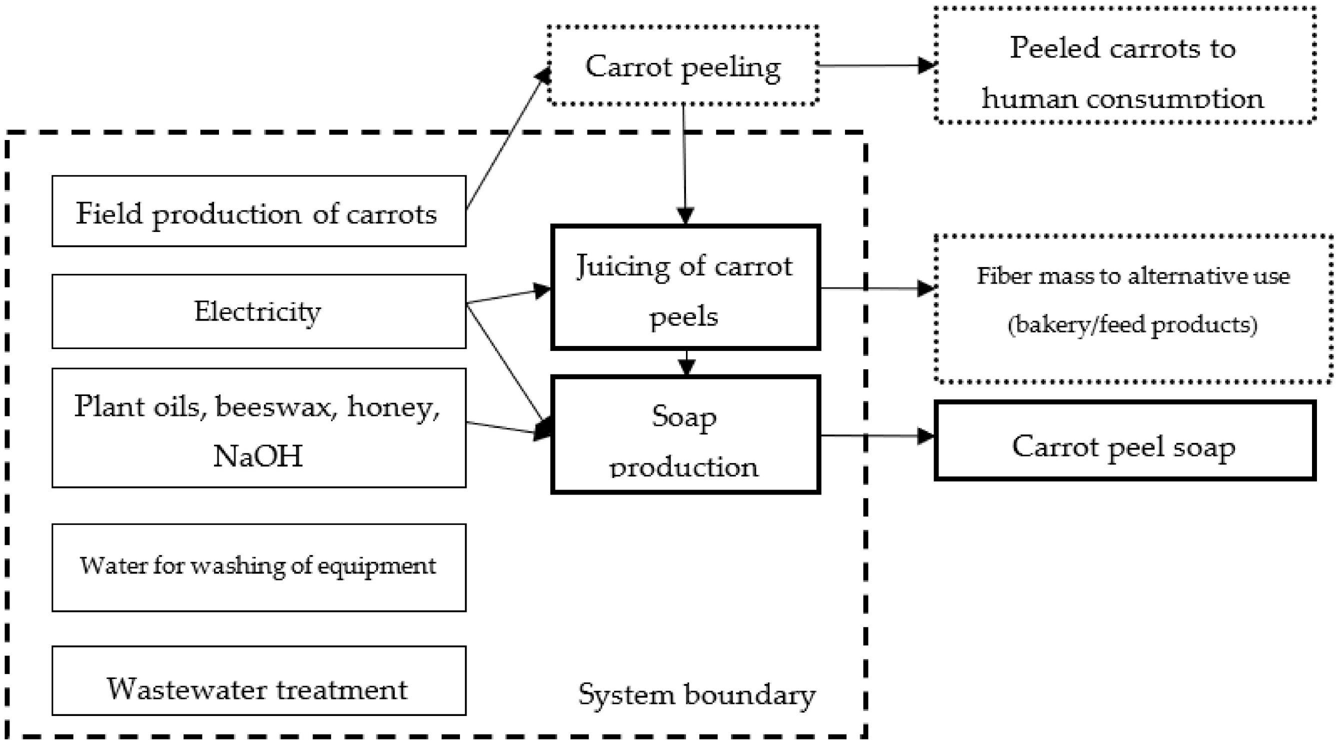

Figure A1. Simplified flowchart of the system boundary of carrot peel soap production from cradle-to-gate.

Figure A2. Carrot peel bar soap product.

A share of the climate impact caused by the field production of carrots was allocated to the production of carrot peel soap based on economic allocation using the assumptions that the share of 2nd class yield in carrot production is 12% [26]. It was also assumed that the economic value of 1st class carrots sold to food use is 0.64 EUR/kg [40] while the economic value of peeled 2nd class carrots is similar to that of fodder carrots, EUR 0.23 per kg [41]. The economic value of carrot peels was assumed to be 10% of 1st class carrots sold to food use. The climate impact of carrot cultivation and beeswax and honey production was estimated according to Räsänen et al. [42], the climate impact of vegetable oils according to Saarinen et al. [43], the climate impact of water for household consumption according to Tenhunen et al. [44] and the climate impact of NaOH and recycled paper for packing the products according to the Ecoinvent 3 database. The climate impact of the transport of the raw materials was assessed based on data available in the Lipasto database [45], assuming road transport with a delivery van. The climate impact of wastewater treatment was also estimated [46]. The climate impacts of soap production were completely allocated to the carrot peel soap, as it was uncertain whether the fiber mass remaining after juicing could be used in another commercial food product in reality.

The climate impact of the studied solutions was compared to a situation where they are not used. In our case example 1, this means that the carrot peels are composted on farm and an alternative soap product is used, in this assessment a coconut and palm oil based bar soap. The emissions of biomass composting were assessed based on the assumptions that half of the biomass nitrogen is released and 5% of the released nitrogen is N_2O. For biomass carbon, it was assumed that 65% is released and 3% of it is methane [47]. Carrot chemical composition values were obtained from Rahn and Lillywhite [48]. The climate impact estimate of the alternative soap product was taken from the Ecoinvent 3 database.

Appendix A.1.3. Retail Selling of 2nd Class Carrots

In case example 2, unpacked 2nd class carrots are sold to consumers in a grocery store. To find out about consumers' willingness to buy 2nd class vegetables, a two-week-long consumer study was carried out in a large grocery store belonging to the S-group in Hämeenlinna, Finland, at the end of November 2018 (19–30 November 2019). The consumer study included branding of the products and consumer information about the opportunity to decrease food waste in the food chain by buying the 2nd class vegetables (Figure A4).

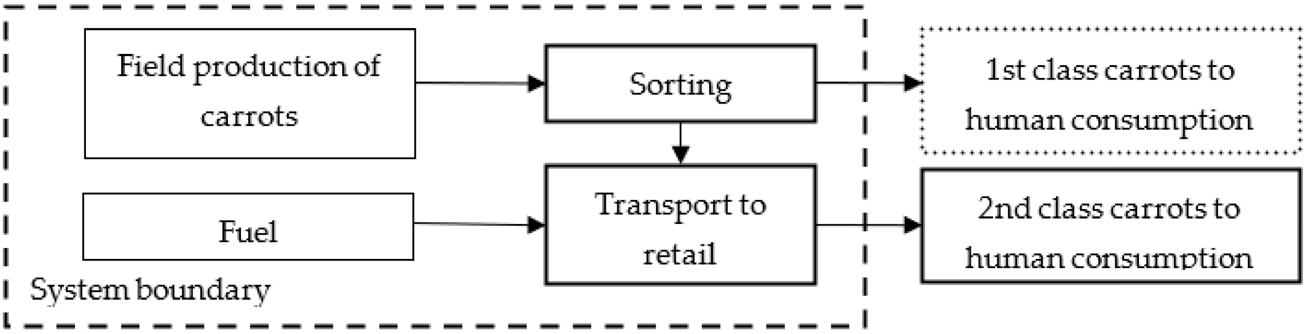

Figure A3. Simplified flowchart of the system boundary of retail selling of 2nd class carrots.

Figure A4. Display of 2nd class vegetables in retail shop during the consumer study.

A share of the climate impact caused by field production of carrots was allocated to the 2nd class yield based on economic allocation using the assumptions that the share of 2nd class yield in carrot production is 12% [26], as in case example 1, but the economic value of the 1st and 2nd class carrots would be 1.98 and 0.99 EUR/kg, respectively (data collected during the consumer study).

The climate impact caused by the transport of the products was assessed estimating that the transportation distance from the farms to the wholesales company distributing the carrots would be ca. 20 km and the distance from the wholesales company to the grocery store would be ca. 71 km (the latter value a direct calculation).

The climate impact of the current case, in which the 1st class carrot yield is sold to retail and the 2nd class carrots are used as feed, was compared to a situation where also the 2nd class was sold to retail.

Appendix A.2. Calculation Details of Economic Impact

Appendix A.2.1. Artisan Bar Soap

There are currently several artisan soap products available on the market (Table A2), but also more industrial bulk products that are sold with remarkably lower prices, such as Rexona bar soap, which is currently sold for only 5.96 EUR/kg (https://www.tokmanni.fi/palasaippua-2-x-125-g-sport-5000186821098, accessed on 13 June 2019). The target consumer group in the present study includes consumers that are familiar with the use of bar soaps, value handmade products and are willing to pay extra for them. Handicraft and naturalness are commonly used ways of differentiating Finnish soap products. We also found one soap product including carrot, which uses information about the skin-nourishing ingredients of carrot in their marketing.

The price of carrot peels was assessed in the same way as for the climate impact assessment (i.e., the 10% of the producer price for 1st class carrots). The costs of other soap raw materials were estimated based on data available in sources mentioned in Table A1. Prices of example alternative artisan soap products are presented in Table A2. The sales revenue of soap production was estimated using the average of the prices of the alternative artisan soap products, ca. 90 EUR/kg. Total costs of soap production were calculated on a monthly basis (Table A3), assuming that 90 pieces of soap (9 kg) would be produced and sold per month.

Table A2. Example artisan soap products available on the market, their prices and marketing arguments.

Artisan Soaps	Price EUR/kg	Marketing Arguments	Source
Carrot vitamin soap	69	- natural - handmade - contains skin nourishing vitamin A and E	https://www.life.fi/Nurme-Carrot-Vitamin-Soap, accessed on 12 June 2019
Shower soap bars	75	- artesan product, every piece is unique - pure, does not contain synthetic chemicals - authentic	https://www.luonteva.fi/tuotteet/luonteva-suihkusaippuat/, accessed on 12 June 2019
Face soap containing birch leaves and seaweed	127.14	- organic - vegan friendly - contains skin nourishing vitamins and minerals	https://www.ruohonjuuri.fi/kasvosaippua-koivu-merileva-madara-4751009822082, accessed on 12 June 2019

Table A3. Estimated costs and sales revenue for soap production.

Variable Costs per Month	EUR/9 kg Soap
Car use	60
Raw materials (from Table A1)	64
Marketing and communication	60
Office costs (use of phone and internet and other office equipment)	80
Material waste related to product development	20
Maintenance of own webstore	29
Total variable cost	313
Sales revenue	810
Profit margin	497

Appendix A.2.2. Retail Selling of 2nd Class Carrots

The target consumer group was consumers that are not so strict in terms of the appearance of the products and are willing to buy carrots that differ from the 1st class in their size and shape. In marketing campaigns for 2nd class products in other countries, the uniqueness and funny appearance of the products has been used in marketing communication, as well as the opportunity to reduce food waste by buying products that would normally not have been used for food [49].

The production cost of carrots for the farmer have been assessed by Kajalo [50] to be ca. 0.631 EUR/kg. The representative of the wholesales company that provided the 2nd class carrots to the consumer survey in the present study reported that additional sorting is needed for separation of the 2nd class carrots from those that are not suitable for human consumption. The producer price of 1st class carrots is ca. 0.640 EUR/kg [40], and the producer price of fodder carrots is ca. 0.23 EUR/kg [41]. In our consumer study, the retail prices of 1st and 2nd class carrots were 1.98 and 0.99 EUR/kg, respectively. If we assume similar difference in the producer prices, the producer price of 2nd class carrots would be 50% of the price of 1st class carrots, making the price 0.32 EUR.

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