



Life cycle assessment and waste reduction optimisation of household food waste in Finland

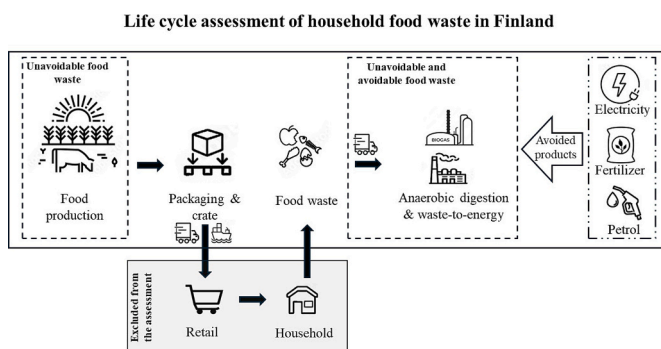
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HIGHLIGHTS

- Agricultural production causes significant environmental impacts
- Environmental benefit of waste treatment depends on the substituted products
- Optimisation problem can be used to devise a reduction strategy
- Edible food waste is associated with resource waste and unethical issue
- Reduction of edible food waste is the key to decrease overall impacts

GRAPHICAL ABSTRACT



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ABSTRACT

This study assessed the environmental impacts of national household food waste in Finland, both the edible (EFW) and inedible (IFW) fractions. The analysis covered the upstream stage, where the food was produced and the end-of-life (EoL) stage, which consisted of waste-to-energy (WtE) and anaerobic digestion (AD). Life cycle assessment with a consequential approach was applied, and a CML baseline was selected as the impact assessment method. An optimisation problem using non-dominated sorting genetic algorithm II was then implemented to investigate the optimum reduction strategy of the EFW. The results showed that the food production stage caused detrimental impacts while the EoL generated environmental benefits due to product substitution. The annual climate change impact from upstream and EoL stages was 0.332 M tonne (Mt) CO₂ eq and – 0.05 Mt. CO₂ eq, respectively. Beef production was an environmental hotspot in the upstream stage that contributed to about 28 % of climate change impact (0.093 Mt. CO₂ eq), although the product was only 3 % of EFW. The hotspots in the EoL stage were energy recovery in WtE (–0.03 Mt. CO₂ eq) and petrol substitution in AD (–0.04 Mt. CO₂ eq). The optimisation minimised the climate change and cost of EFW when a 50 % reduction was achieved. The optimised solutions decreased 59.5 % climate change impact and 54.6 % cost. The research underlined the

Abbreviations: AC, Acidification; AD, Anaerobic digestion; AD, Abiotic depletion; AD-FF, Abiotic depletion fossil fuel; APC, Air pollution control; CC, Climate change; EFW, Edible food waste; EoL, End-of-life; EU, Eutrophication; FU, Functional unit; FW, Food waste; FWE, Freshwater aquatic ecotoxicity; HT, Human toxicity; IFW, Inedible food waste; LCA, Life cycle assessment; LCT, Life cycle thinking; MAE, Marine aquatic ecotoxicity; MOO, Multi-objective optimisation; NDS, Non-dominated sorting; NSGA-II, Non-dominated sorting genetic algorithm II; ODP, Ozone layer depletion; PO, Photochemical oxidation; TE, Terrestrial ecotoxicity; WtE, Waste-to-energy.

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importance of quantifying the impacts of food waste as the first step for devising targeted interventions which can be implemented throughout the food supply chain.

1. Introduction

Food waste (FW) has emerged as a critical global challenge, posing significant environmental, economic, and social pressure. It was reported that about 14 % of global food production is lost before reaching the retail stage, while 17 % is wasted in households, food service and retail (FAO, 2019; UNEP, 2021). The 17 % global food production equals 931 million tonnes of FW, whereas households waste around 570 million tonnes. Moreover, the global population is projected to reach 9.7 billion by 2050, necessitating a significant increase in food production (European Commission, 2022a).

FW is commonly distinguished between the avoidable and unavoidable. The former is also called edible food waste (EFW); the latter is known as inedible food waste (IFW). EFW refers to the food that could have been consumed before being discarded, while IFW is the food that could not have been consumed, such as peeling, bones, coffee grounds, etc. (Östergren et al., 2014). The EFW represents a squander of resources as agricultural production requires energy, water, chemicals, land, and other inputs. That loss translates into substantial environmental impacts such as climate change, acidification, eutrophication, ozone layer depletion, depletion of natural resources and loss of biodiversity (Brancoli et al., 2017) that ideally should not occur. Moreover, EFW increases the demand for waste treatment because of its high volume, making FW reduction important to ensure food security and environmental and economic safeguards. The focus on reducing avoidable food waste presents a significant opportunity to minimise environmental impact.

Households, which contributed about 11 % to global food waste (UNEP, 2021), were one of the hotspots of FW during the supply chain. Assessing household FW is important to provide public knowledge about the problem and assist in devising an EFW reduction strategy. The assessment can be done using the life cycle thinking (LCT) approach. LCT embodies the core principle of evaluating the environmental impacts of products, sectors, or projects from a holistic standpoint, spanning from the extraction of raw materials to their eventual disposal (Sala et al., 2021). The LCT principle can be employed using life cycle assessment (LCA), a quantitative tool to calculate environmental impact from cradle-to-grave covering a broad range of impact categories.

This study aims to assess environmental impacts of household FW in Finland using LCA and demonstrate the application of multi-objective optimisation within the LCA context to optimise FW reduction strategy. It included upstream and end-of-life (EoL) stages, which, to the author's knowledge, had not been done before at the national level in Finland. Silvennoinen et al. (2022) estimated the impact of climate change associated with FW in Finland, but the study did not cover other impact categories and the EoL stage. This study also assessed the impacts based on food categories for the upstream stage and the impacts of different activities during the treatment phase. The approach taken by build own LCA model using the consequential system model of the Ecoinvent 3.8 database will ensure consistency compared to collecting emission factors from various sources, which is a decent approach that may be produced using different system models (e.g., consequential, cut-off, or allocation at the point of substitution). The goal of this study is achieved by applying LCA and optimisation to: i) assess the environmental impacts of EFW and IFW, ii) assess the environmental hotspot and model behaviour through scenario analysis, iii) demonstrate how optimisation could be used for reduction strategy.

2. Material and methods

The study assessed the environmental implications of household food

waste (FW) in Finland and its reduction strategy. The basis of this research was the FW quantities and categories that were taken from a previous study applying waste composition analysis (WCA) to three different cities in Finland, namely Helsinki, Turku, and Tampere, covering about 98,000 inhabitants (Silvennoinen et al., 2022). Their study included urban and suburban areas and housing types, such as detached houses, small houses, and apartment complexes. Due to the harsh winter, most agricultural and food products in Finland are imported from other countries. The agricultural practices adopted by the exporters and the transportation mode affect the environmental impacts of the food. The impacts were also affected by waste treatment options, encompassing anaerobic digestion (AD) and waste-to-energy (WtE). In Finland, properties in urban areas with at least five apartments should arrange source-separated biowaste collection (European Environment Agency, 2022). Sourced-separated biowaste is treated in AD; meanwhile, properties with fewer than five apartments will dispose the biowaste as the mixed waste fraction to be treated in the WtE plant.

2.1. Goal and scope definition

The study quantified the environmental impacts of food waste, both the edible food waste (EFW) and the inedible food waste (IFW). The waste fractions and quantities were based on a previous study on household food waste in Finland done by Silvennoinen et al. (2022), in which the average results of food waste (FW) per capita can be upscaled to estimate the impacts of FW on a national scale. These FW fractions were vegetables, potatoes, fruits, apples from their garden, pasta and rice, bread, meat and fish, cheese and dairy, and others. Silvennoinen et al. (2022) quantified FW generation and its climate change impacts at the production level. This study applied LCA to consider impact categories other than climate change to gain better insights regarding the environmental implications of FW. Moreover, this study expanded into the downstream stage or waste treatment phase. The functional unit of the study (FU) is the total waste households generate in a year. The choice of the FU was based on the study's aim to investigate the overall environmental impacts of household food waste nationally. A similar approach was found in Brancoli et al. (2017), who picked overall food waste generated in a year, although they focused on the retailers sector.

2.2. System boundaries

A simplified flow diagram of the food life cycle is shown in Fig. 1. The boundaries of the study were defined as: i) upstream, which covered the impacts of the production of food (e.g., land preparation, animal feed, fertiliser production, heat, water consumption, all inputs and outputs from bread and pasta making, etc.), packaging, reusable plastic crates, and transportation to retailers; ii) downstream, which was end-of-life stage where FW was transported and treated by AD and WtE.

Since the study focused on the FW, not the food system itself, the upstream phase covered only the EFW to focus on the impacts that can be avoided. Unlike the upstream stage, the EoL assessed the impacts of both EFW and IFW. The IFW would always be generated; hence, resources were always consumed, and impacts occurred when treating the IFW. The impacts from retail storage, shopping trips, supermarket waste, consumer storage, and food cooking were not included (the grey area in Fig. 1). More details of the EoL stage are shown in the Supplementary material Figs. 1 and 2.

A consequential approach was applied to handle co-products generated from the waste treatment process. A consequential LCA describes how the impacts change in response to any decision (Ekvall, 2020). Within the context of the study, the consequential approach

refers to expanding the system to include the processes affected by the studied system. During the waste treatment, WtE and AD generated multiple outputs. WtE generated electricity and heat that were assumed to supply the energy to the WtE plant and grid. Meanwhile, the AD generated biogas and digestate to substitute petrol and inorganic-N fertiliser. Therefore, some of the impacts of producing electricity, petrol, and fertiliser can be avoided. In doing so, the system in the study was expanded into energy generation, petrol production, and fertiliser production, although the system boundaries did not directly cover them (see Fig. 1).

2.3. Inventory analysis

The data used in this study were collected from various sources combined with Ecoinvent database version 3.8 (Ecoinvent, 2021). A study done by Silvennoinen et al. (2022) provided information regarding the average waste quantities of EFW and IFW in Finland, which were around 24.9 kg/cap/year and 31.5 kg/cap/year, respectively. The study also reported the quantities of EFW based on food categories: vegetables, potatoes, fruits, bread, rice and pasta, dairy products, meat and fish, apple (garden), and others. Others fraction is defined as a combination of different foods. It can be home cooked food, cereal products other than bread, pastries, takeaway, canned food, or confectionary products. The summary of annual FW quantity taken from Silvennoinen et al. (2022) is shown in Table 1.

In determining the upstream impacts, weighted average impacts of FW fraction were applied. The food categories can be divided into more detailed agriculture products based on the most consumed products and their country of origin. One main importing country was selected where the same product came from multiple countries.

The inventory data of agricultural production was obtained from different sources. The main means to assess the environmental impacts of food production was using processes available in the Ecoinvent database combined with inventory from specific countries. The process that was not available in the database was modelled in the software using literature, such as bread and pasta (Cámara-Salim et al., 2020; Gnielka and Menzel, 2021). Some vegetables grown in Finland were modelled using Finnish literature because they consume significantly more energy than greenhouses in other countries, such as The Netherlands (Frans and Juha-Matti, 2021). More detailed information regarding agricultural products and their country of origin can be found in the Supplementary Material Table 1.

The distance of land transportation to retailers was approximated. Meanwhile, the sea distance from one port in the country of origin to Naantali port in Finland was calculated. Refrigerated lorry and shipping were assumed for the perishable product, while dry products such as pasta were transported using a non-refrigerated system. The information about the country of origin of each product was obtained from

Silvennoinen et al. (2022) and OEC (2023). The packaging type and its weight were adapted from Brancoli et al. (2017) and own measurement of the typical Finnish food packaging. The crates used to transport the food were also included and modelled based on a previous study (Tua et al., 2019). It was a reusable plastic crate (RPC) that could be used 125 times. Complete information regarding transportation, packaging, and crate needed can be found in Supplementary material Tables 2 and 3.

At the EoL, FW was treated in AD and WtE, in which the source-separated biowaste fraction will be treated in AD, and the ones being disposed of as mixed fraction will be treated in the WtE plant. Each municipality in Finland has a different level of source-separated biowaste, and not all the information is available. Circwaste and Plastlife (2022) reported the percentage of source-separated biowaste in ten municipalities in Finland. The median of those data was 44 %, which was applied as the national level of source-separated biowaste in this study. Hence, the remaining 56 % of biowaste was assumed to be treated in the WtE plant. The complete inventory concerning EoL treatment is shown in Supplementary material Tables 5 and 6.

When selecting the data, relevance, consistency, and accuracy were considered. The data should be of geographical, technological, and temporal relevance. In this case, the FW quantities and fractions were from a Finnish study between 2015 and 2019, covering different cities, housing types, and disposal methods (Silvennoinen et al., 2022). A priority tier regarding data availability was applied to ensure relevance and consistency. The data should reflect the situation in i) Finland, ii) Nordic, iii) Europe, or iv) other countries globally. When Finnish data is unavailable, the Nordic context was used because there are similarities among countries within the region, such as the demographic or climate (e.g., the energy needed to grow vegetables in a greenhouse). European data is the next tier. Although Europe is quite big and consists of many countries, most of them are EU members, which makes them subjected to similar regulations and directives, leading to a certain level of convergence. Other countries globally are in the last tier when all else is unavailable. For example, the impacts of vegetable production were calculated using Finnish inventory data when available (e.g., Frans and Juha-Matti, 2021) since the study showed higher energy consumption than Ecoinvent inventory using data from other regions. Information about inventory is in supplementary material Table 1. The data for modelling the EoL using AD and WtE was also based on its relevance to Finland (Circwaste and Plastlife, 2022). The operational data in the AD and WtE were from the Finnish study; otherwise, the priority tier was applied. The accuracy was also ensured by considering the biowaste type treated by AD and WtE since they affected the biogas, electricity, and emission generation. Meanwhile, the consistency of the methodological approach was supported by using Ecoinvent consequential.

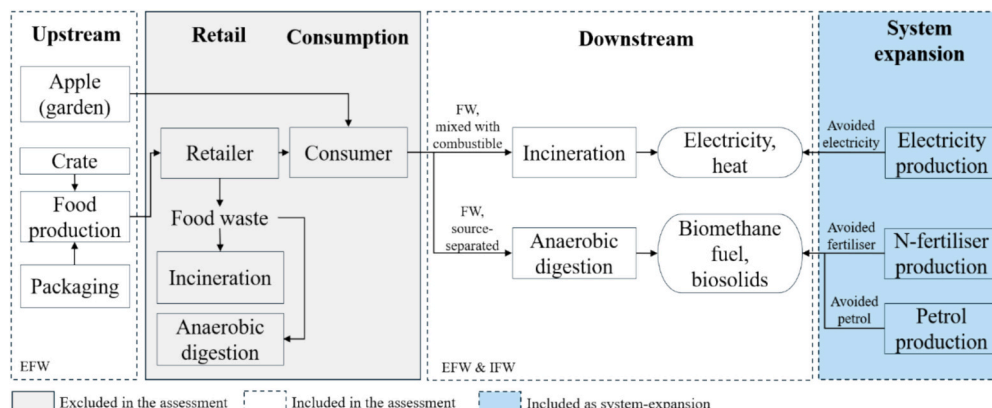


Fig. 1. Flow diagram of food life cycle stage.

2.4. Impact assessment

Tools called waste incineration life cycle inventory (WILCI) (Beylot et al., 2017) and OpenLCA software were applied to conduct LCA. WILCI was used to generate emissions inventories from WtE, which allowed for the adjustment of waste composition, air pollution control equipment, ash handling, and energy recovery. The inventories generated by WILCI were keyed into the OpenLCA to determine impact categories. Meanwhile, the other processes were modelled using OpenLCA. Mid-point impact categories were calculated using CML-baseline (CML, 2016). The method was used because it is relevant to the European context, and the selection of the mid-point impact categories provided sufficient information without being exhaustive. These impacts are abiotic depletion (AD), abiotic depletion for fossil fuels (AD-FF), acidification (AC), eutrophication (EU), freshwater aquatic ecotoxicity (FEW), climate change (CC), human toxicity (HT), marine aquatic ecotoxicity (MAE), ozone layer depletion (ODP), photochemical oxidation (PO), and terrestrial ecotoxicity (TE). More focus was given to CC because of its urgency and effects to the global population.

In addition, a contribution analysis was implemented to assess the environmental hotspots. It made it possible to obtain insights regarding the parts of the system that caused the highest impact. The analysis can be done based on the food type to investigate which food causes the highest climate change impacts. The analysis can also be done based on the key activities. For example, which activities in the upstream stage (food production, transportation, packaging use, and crate use) are causing the environmental hotspots. The same approach was applied to the EoL by identifying environmental hotspots based on key activities during waste treatment. The main activities during waste treatment using AD were plant construction, transportation to the plant, digestion process, biogas upgrading, digestate application, avoiding fertiliser production, and avoiding petrol production. Meanwhile, WtE's key processes were plant construction, transportation to the plant, direct emission (from incinerating), bottom ash management, reagent consumption, air pollution control (APC) residue management, water and energy for pollution reduction, and energy consumption and recovery.

2.5. Scenario analysis

Different scenarios are applied to explore how the results change under different circumstances. Three scenarios included i) reduction of crate reuse to 100 times, ii) the food produced was transported from Finland (local), and iii) 70 % of FW was treated in the AD. The scenarios can provide good insight into how the model behaves and how the

Table 1
Summary of FW quantity.

Food waste type	Value	Unit
EFW	138,404	tonne
Vegetables	24,342	tonne
Potato	10,850	tonne
Fruit and berries	14,188	tonne
Bread	21,978	tonne
Rice and pasta	3477	tonne
Cheese and other dairy	7650	tonne
Meat and fish	14,745	tonne
Others	32,967	tonne
Apple (garden)	8207	tonne
IFW	171,604	tonne

Table 2
Overall impacts from annual food waste.

Impact categories	Overall impact	Unit
Abiotic depletion	5.12E+03	kg Sb eq
Abiotic depletion (fossil fuels)	2.06E+09	MJ
Acidification	2.70E+06	kg SO ₂ eq
Eutrophication	1.28E+06	kg PO ₄ eq
Freshwater aquatic ecotoxicity	2.57E+08	kg 1,4-dB eq
Climate change	2.83E+08	kg CO ₂ eq
Human toxicity	3.06E+08	kg 1,4-dB eq
Marine aquatic ecotoxicity	1.91E+11	kg 1,4-dB eq
Ozone layer depletion (ODP)	1.56E+01	kg CFC-11 eq
Photochemical oxidation	5.65E+04	kg C ₂ H ₄ eq
Terrestrial ecotoxicity	2.16E+07	kg 1,4-dB eq

Table 3
Total environmental impacts of EFW production.

Name	Impact result	Unit
Abiotic depletion	5.60E+03	kg Sb eq
Abiotic depletion (fossil fuels)	2.72E+09	MJ
Acidification	2.82E+06	kg SO ₂ eq
Eutrophication	1.33E+06	kg PO ₄ eq
Freshwater aquatic ecotoxicity	2.70E+08	kg 1,4-dB eq
Climate change	3.32E+08	kg CO ₂ eq
Human toxicity	3.11E+08	kg 1,4-dB eq
Marine aquatic ecotoxicity	2.32E+11	kg 1,4-dB eq
Ozone layer depletion	2.24E+01	kg CFC-11 eq
Photochemical oxidation	6.23E+04	kg C ₂ H ₄ eq
Terrestrial ecotoxicity	2.16E+07	kg 1,4-dB eq

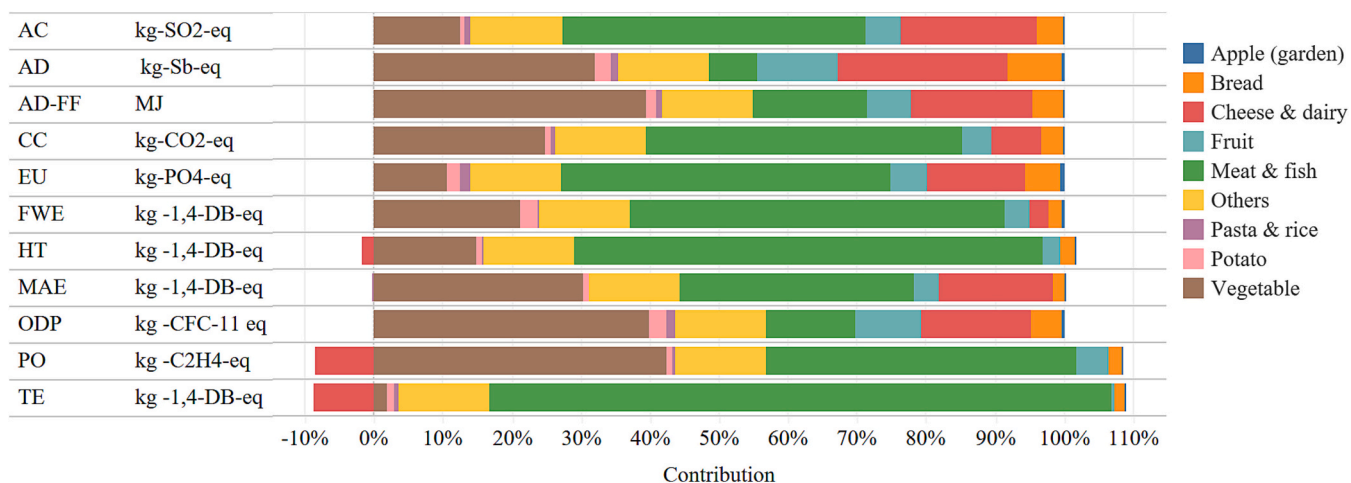


Fig. 2. Relative contribution of each EFW fraction to acidification (AC), abiotic depletion (AD), abiotic depletion fossil fuel (AD-FF), climate change (CC), eutrophication (EU), freshwater aquatic ecotoxicity (FWE), human toxicity (HT), marine aquatic ecotoxicity (MAE), ozone layer depletion (ODP), photochemical oxidation (PO), terrestrial ecotoxicity (TE).

background system affects the environmental impacts compared to the baseline. The first and second scenarios focused on the upstream stage, while the third scenario focused on the EoL stage. In the second scenario, the focus was on transportation without changing the agricultural production of the food. The third scenario increased the FW treated in AD from 44 % to 70 %. Available data gathered by [Circwaste and Plastlife \(2022\)](#) showed the rate of source-separated biowaste in various areas in Finland ranged between 34 %–70 %, with a median of 44 %. The baseline study applied a value of 44 % as a proportion of FW treated by AD, while the scenario analysis used a value of 70 % since it was the highest value found in Jyväskylä area; the value was deemed plausible to attain by other areas.

2.6. Optimisation problem

Optimisation problem deals with identifying the optimal feasible solution among a set of possible solutions for a given problem ([Sharma et al., 2012](#)). Often, there is more than one objective to optimise, which may conflict with each other; therefore, multi-objective optimisation (MOO) is applied ([Deb, 2011](#)). Within the context of sustainability, research on integrating optimisation problem and LCA was not new. In the nineties, linear programming was integrated into LCA to manage the environmental performance of product systems ([Azapagic and Clift, 1995](#)). Nonetheless, combining LCA and MOO is still uncommon. It is not supposed to replace scenario analysis since it deals with a broader context, whereas optimisation involves a more detailed level; it can quantify the change needed to obtain optimal results.

This study implemented MOO to identify the optimal FW reduction strategy using the Finnish target to reduce FW by 50 % in 2030 ([European Commission, 2023](#)). To illustrate how the optimisation problem can be paired with LCA to achieve the optimum reduction strategy, MOO was applied to identify the most optimum solutions to different reduction targets of 15 %, 25 %, and 50 %. The objectives of the optimisation were to minimise climate change impact and costs associated with EFW as shown by eqs. (1) and (2):

$$\text{Minimise } CC = \sum_{n=1}^n CC_n \cdot m_n \quad (1)$$

where *CC* refers to climate change impact, *n* represents different EFW fractions (potatoes, vegetables, etc.), and *m* is the weight of each EFW fraction.

$$\text{Minimise } Cost = \sum_{n=1}^n P_n \cdot m_n \quad (2)$$

in which *Cost* represents misspent money associated with EFW and *P* is the purchasing price of the food. Nine decision variables were applied; they represent the weight of each EFW fraction (*m_n*). The price of the food is in supplementary material in [Table 4](#).

The optimisation was conducted using Ms. Excel tool developed and improved by [Sharma et al. \(2012\)](#) and [Wong et al. \(2016\)](#). It employs a

Table 4
Total environmental impacts of FW treatment.

Name	Impact result	Unit
Abiotic depletion	-4.75E+02	kg Sb eq
Abiotic depletion (fossil fuels)	-6.65E+08	MJ
Acidification	-1.22E+05	kg SO ₂ eq
Eutrophication	-5.59E+04	kg PO ₄ eq
Freshwater aquatic ecotoxicity	-1.25E+07	kg 1,4-dB eq
Climate change	-4.92E+07	kg CO ₂ eq
Human toxicity	-4.71E+06	kg 1,4-dB eq
Marine aquatic ecotoxicity	-4.05E+10	kg 1,4-dB eq
Ozone layer depletion (ODP)	-6.81E+00	kg CFC-11 eq
Photochemical oxidation	-5.84E+03	kg C ₂ H ₄ eq
Terrestrial ecotoxicity	-3.65E+04	kg 1,4-dB eq

non-dominated sorting genetic algorithm II (NSGA-II), where the search method simulates the natural selection process to generate global optimisation results. The study implemented a maximum number of generations as termination criteria, set to 500 generations. The optimisation was run five times, and all the solutions were combined for calculation using Ms. Excel tool for non-dominated sorting (NDS) to generate the most desirable solution ([Sharma et al., 2017](#)).

3. Results

3.1. Overall impacts

[Table 4](#) shows the overall impacts of FW, which is the sum of the impacts from the upstream and EoL stages. The overall climate change impact was 0.28 megatonnes (Mt) CO₂ eq, in which EFW production contributed about 0.332 Mt. CO₂ eq, showing that the benefits from EoL treatment were only 15 %. The environmental hotspots across all impact categories are visualised in the Supplementary material [Fig. 3](#).

The details of the impacts caused by the upstream and downstream processes are presented in the following subsections.

3.1.1. Impacts of the EFW production (upstream)

The total EFW in a year was about 138,404 t, categorized as apple (garden), bread, cheese and other dairy, fruit, meat and fish, potato, pasta and rice, vegetables, and others. For more detailed impact calculation, some fractions were further characterised into several sub-types of food fractions based on the highly consumed products ([Silvennoinen et al., 2022](#)). The fruit fraction consisted of banana, orange, apple, and melon; the vegetable fraction included pepper, lettuce, cucumber, and tomato; the meat fraction comprised beef, pork, chicken, and fish (Supplementary material [Table 8](#)). The quantity of the sub-types was equal for each waste fraction since it was calculated by dividing the fraction by the number of sub-product types. The EFW impact is shown in [Table 3](#).

The relative contribution of analysis was made to investigate environmental hotspots, as shown in [Fig. 2](#). For three impact categories (AD, AD-FF, and ODP), the production of vegetables, which contributed to 17.6 % of the waste, had the highest impact. In comparison, meat and fish production were the hotspots in the other eight impact categories. In the meat and fish category, beef production was the main cause of the impact, although it only covered almost 3 % of the EFW weight. The opposite trend was shown by bread, which did not cause a high impact during production, although it contributed to 16 % of the total waste by mass. The emission factor per kg of different food types can be found in the Supplementary material [Table 7](#).

The climate change was investigated further, as displayed in [Fig. 3](#). The production stage contributed the highest impact, except for the fruit, for which transportation was the environmental hotspot. The fruits consumed in Finland are mainly imported, including bananas from Costa Rica. Consistent with [Fig. 2](#), meat and fish caused the highest impact of 145,058 t of CO₂ eq. The highest impact was caused by beef, contributing to 28 % of total emissions or 93,151 t of CO₂ eq (including transportation, packaging, and crate) despite the low mass fraction of 3686 t. Vegetables were another climate change hotspot, where lettuce emitted 24,008 t of CO₂ eq. (7.23 % of the total impact). [Fig. 3](#) is complemented by detailed results of climate change impacts on EFW as shown in Supplementary material [Table 8](#).

3.1.2. Impacts of waste treatment (downstream)

The total FW, from the EFW and IFW, was about 310,008 t. AD treated 44 %, and WtE treated 56 % of the total FW. [Table 4](#) shows the total impacts of waste treatment, where the negative results indicated benefits from avoided products outweighed the detrimental impacts during treatment. The contribution from AD and WtE to the total impacts varied. AD and WtE contributed fairly equally to abiotic depletion and acidification. WtE contributed more than 70 % of total impacts in

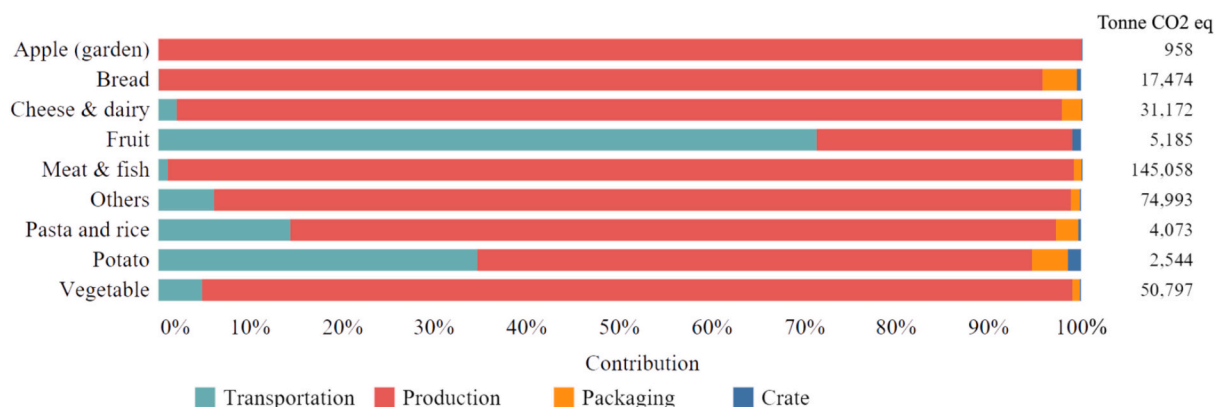


Fig. 3. Relative contribution of upstream stage and total climate change impact.

eutrophication, freshwater ecotoxicity, marine aquatic ecotoxicity, and photochemical oxidation. Meanwhile, AD contributed more than 60 % for the rest of the categories.

Detailed contributions of climate change impacts can be found in Fig. 4. The overall climate change impact of AD and WtE were $-3.02E+07$ kg CO₂ eq and $-1.90E+07$ kg CO₂ eq, respectively. The main benefit of AD was the upgraded biogas used as vehicle fuel; hence, it replaced petrol. In comparison, WtE recovered electricity for its use in the plant and the grid, generating environmental benefits by avoiding electricity generation from the electricity mix. The study showed that biowaste treatment using AD provided higher benefits than WtE, implying the importance of separating biowaste from the source. The climate change impact of treating one-tonne biowaste in AD and WtE generated around -221 kg CO₂ eq and -110 kg CO₂ eq, respectively. Fig. 4 is complemented by the impacts caused by per tonne FW

treatment in AD and WtE, as shown in the Supplementary material Table 9.

3.2. Scenario analysis

Different trends were found in the scenario analysis results (Fig. 5). Fig. 5 shows the percentage difference between the three scenarios with a baseline in each impact category. The baseline scenario was not labelled since it will show 0 %; meanwhile, the other scenarios were labelled by the percentage difference. When the crate was reused 100 times, there was an increase in all the impacts without burden shifting. The impact change in the first scenario ranged between 0.1 %–3.3 %. The highest increase of 3.3 % was from ODP, followed by a 2.9 % increase for AD-FF compared to the baseline scenario. The smallest change of 0.1 % was found in TE. All the impacts decreased in the second

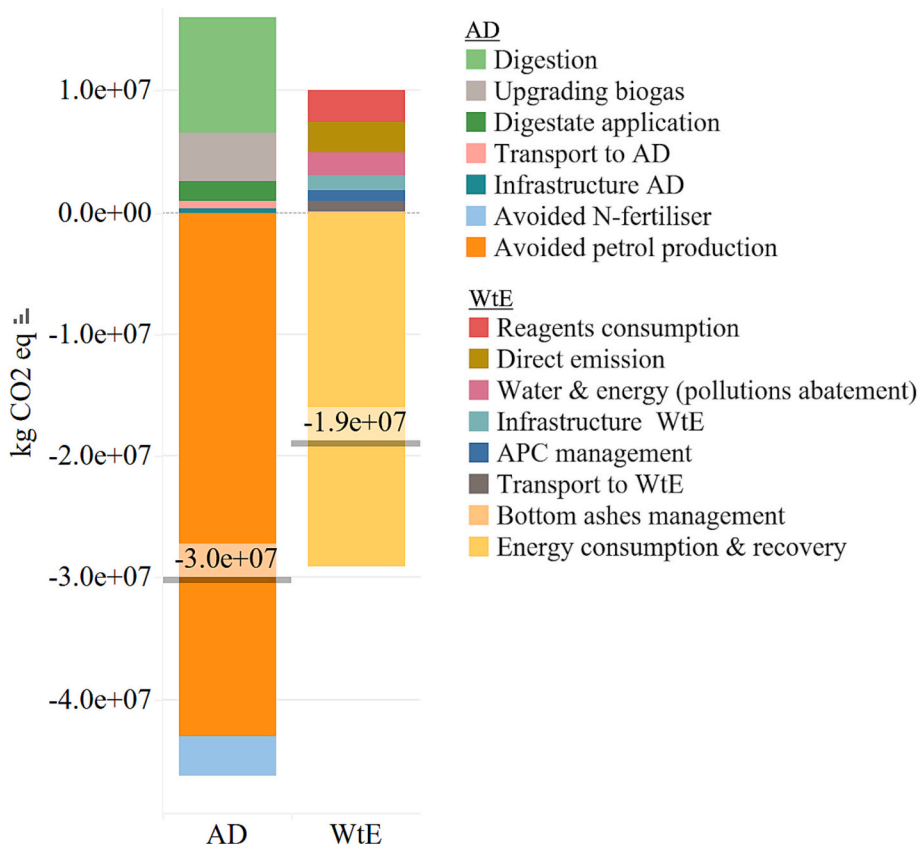


Fig. 4. Contribution on climate change impact of waste treatment in WtE and AD.

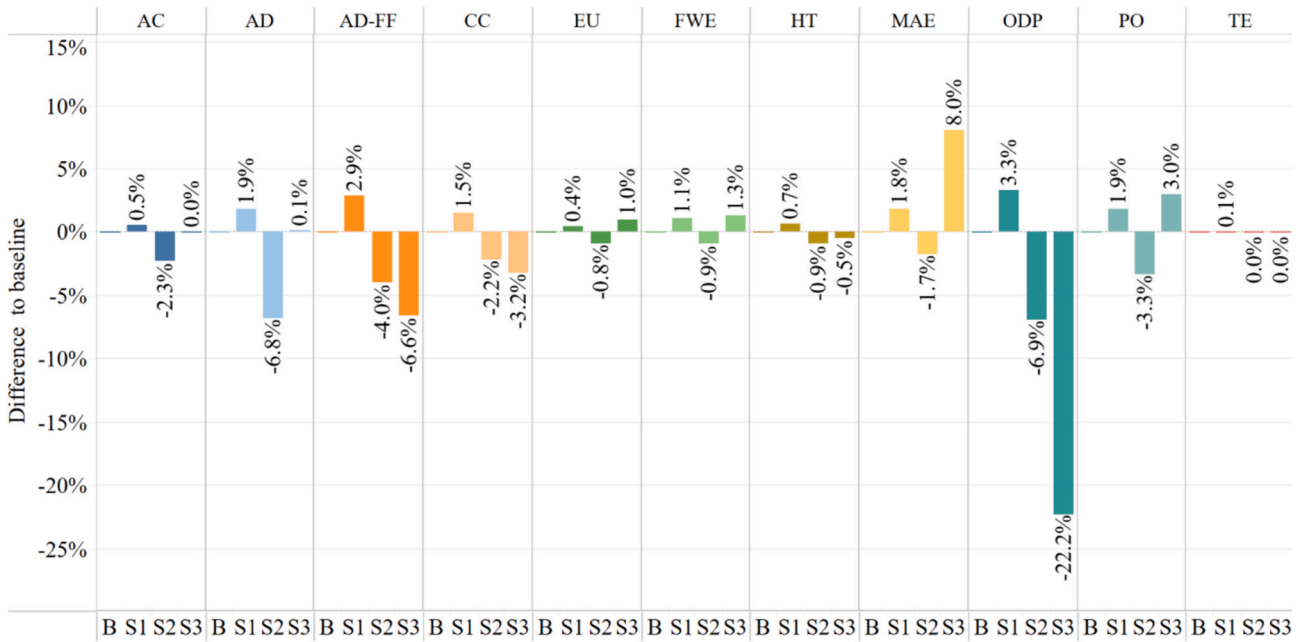


Fig. 5. The results of scenario analysis to different impact categories. The codes on the x-axis indicate: B: Baseline, S1: The crate use for 100×, S2: The food transported from FI, and S3: 70 % FW treated in AD.

scenario, where the foods were assumed to be from Finland. The lowest change was around -0.04% , while the highest was almost -7% . Similar to the first scenario, there is very little change in TE (-0.04%).

The highest change of -7% was found in ODP and AD. The third scenario, 70 % of FW treated in AD, caused a burden-shifting among impact categories, as shown by the change between 8% and -22% compared

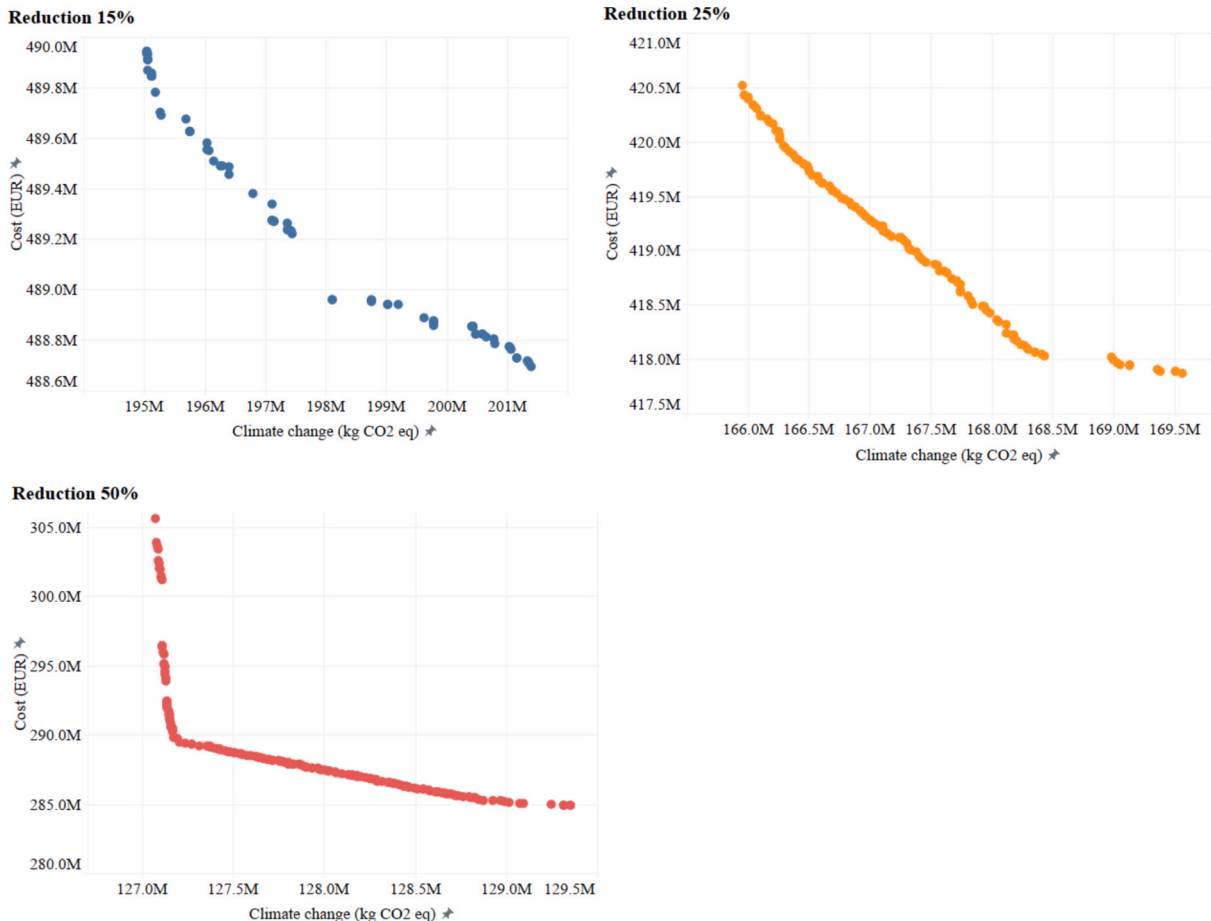


Fig. 6. The true Pareto-optimal front in minimising climate change and cost for a different reduction target.

to the baseline. The highest impact reduction was found in ODP (−22 %), followed by AD-FF (−6.6 %); meanwhile, MAE showed the highest impact increase (8 %), followed by PO (3 %). The TE in the third scenario showed negligible change compared to the baseline.

Scenario analysis explained how the outcomes may shift due to different circumstances. When burden shifting occurs, as shown by the third scenario, relevant stakeholders should consider the relative importance of different impact categories during decision-making. The complete scenario analysis results are in the Supplementary material Table 10.

3.3. Optimisation problem for reduction strategy

The optimisation was applied to achieve a reduction target of 15 %, 25 %, and 50 %. The reduction target indicated overall mass reduction, while each fraction of EFW can be reduced differently. The optimisation was run five times for each reduction strategy. Multiple optimal solutions, also called non-dominated or Pareto-optimal solutions, were generated in each run where each was superior in at least one objective but inferior in at least one other when compared to another solution. To generate the most desirable solutions, also called true Pareto-optimal front, non-dominated solutions obtained from five runs were consolidated and sorted. The process was done for 15 %, 25 %, and 50 % reduction targets, generating 80, 112, and 164 true Pareto-optimal fronts, as shown in Fig. 6. The figure also indicates the trade-offs of minimising the costs and climate change impacts in each reduction strategy.

Table 5 shows the first Pareto-optimal front generated from the consolidation and sorting process. The first Pareto-optimal front was considered the best possible solution numerically (Sharma et al., 2017). Nevertheless, related stakeholders may have certain objectives; hence, decision-making may not apply the first Pareto-optimal front but other solutions within the set of true Pareto-optimal front.

The first optimisation achieved a 15 % EFW reduction while decreasing climate change impact and unnecessary costs by 37.8 % and 27.2 %, respectively. The second target reduced 25 % of EFW whilst reducing 47.1 % of climate change impact and 37.5 % of costs. The last optimisation reduced 50.1 % EFW, which led to a decrease of 59.5 % in climate change and 54.6 % misspent costs. It was found that doubling the target (e.g., from 25 % to 50 %) did not mean doubling the implications of costs and climate change impacts. The first reduction of 15 % could achieve a significant reduction, followed by a less steep reduction when the target was increased.

4. Discussions

4.1. Food waste generation

This study employed 24.9 kg/cap/year EFW and 31.5 kg/cap/year IFW, totalling 56.4 kg waste. In general, household waste sorting analysis will generate lower results than actual waste since the analysis is done only on waste discarded in bins. Part of the waste discarded in

Table 5
Best possible solutions for each EFW fraction.

Food	Baseline (tonne)	Optimised (tonne)		
		15 %	25 %	50 %
Vegetables	24,342	23,984	23,015	9744
Potato	10,850	10,814	10,815	7826
Fruit and berries	14,188	14,181	14,180	11,687
Bread	21,978	21,966	21,919	8803
Rice and pasta	3477	3439	3472	1400
Cheese and other dairy	7650	3065	3063	3062
Meat and fish	14,745	5901	5899	5899
Others	32,967	26,057	13,188	13,189
Apple (garden)	8207	8189	8202	7487

sinks, toilets, fed to animals, and other pathways cannot be captured. It was estimated that liquid waste discarded in sinks or toilets per year per person could amount to up to 57.3 l (van Dooren et al., 2019). Compared to other European counterparts, similar findings were found in Table 6. Finland generates FW within the range of other European counterparts.

The high proportion of EFW, ranging from 45 % to 67 %, was translated into something bigger. These foods were supposed to be consumed but ended up being disposed of. Producing food requires resources; hence, food waste is resources wasted, going beyond environmental and economic costs to social and ethical issues regarding food security on a global level. The depleted resource during agricultural production contributes to climate change that disproportionately affects developing countries (WEF, 2023). The EFW drives global food demand, leading to overproduction, which in some cases is an important measure to reduce the risk of food insufficiency. However, the high demand is known as one of the causes of price volatility (Brief, 2024), which unfairly affects developing nations. The food chain is an interconnected system; actions done by one nation can significantly impact the other part of the world or even disable others from doing something. The fact that 300 million people are in chronic hunger (WFP, 2022), while other countries can afford to waste their edible food, shows a disparity in wealth and resource distributions as well as unethical issues.

4.2. LCA results

Directly comparing LCA results with other studies could be difficult because of different foreground and background data, assumptions, and chosen methods. This study employed a consequential approach, utilizing data from previous studies and Ecoinvent 3.8. Collecting emission factor (EF) from different studies is a common and acceptable practice that will result in decent outcomes. However, studies may apply different methods (e.g., cut-off and consequential approach) with various underlying assumptions and outcomes. Silvennoinen et al. (2022), in which the FW quantities and compositions were used for this study, estimated that the climate change impact of EFW production was 0.314 Mt. CO₂ eq without packaging and crate. This study showed the annual climate change impacts associated with agricultural production of EFW was 0.328 Mt. CO₂ eq (without packaging and crate) and 0.332 Mt. CO₂ eq (including packaging and crate). The difference in climate change impact was only 4.4.% but translated into 13,967 t.

Another important aspect was the impact of local production. Growing vegetables in Finland generates higher impacts since greenhouse production in a cold climate requires a lot of energy (Frans and Juha-Matti, 2021). Imported products required further transportation, but the overall impacts were more favourable than locally grown products. This study showed that kg CO₂ eq of producing 1 kg of tomato, lettuce, and cucumber were 1.4, 3.8, and 1.9, respectively. In comparison, the climate change of tomato production in open fields and greenhouse methods in Italy and Spain was 0.2–0.24 kg CO₂ eq (Bartzas et al., 2015). The impacts of lettuce and cucumber per kg were about 0.13 kg CO₂ eq and 0.5 kg CO₂ eq, respectively (Ecoinvent, 2021).

Previous studies on FW treatment mainly covered AD since the WtE study used mixed waste as inputs. A straightforward comparison of LCA results was difficult since the parameters applied are different, especially the assumption of avoided products that provide environmental

Table 6
Food waste comparison in Europe.

Country	kg/cap/year			References
	EFW	IFW	Total FW	
Denmark	27	21	48	Edjabou et al. (2016)
Finland	24.9	31.5	56.4	Silvennoinen et al. (2022)
Netherlands	41.2	20.6	61.8	van Dooren et al. (2019)
Norway	46.3	33.9	80.2	Hanssen et al. (2016)
Poland	28.6	33.1	61.7	den Boer et al. (2023)

benefits. For the WtE, the environmental benefit was from recovered electricity and heat used in the own plant and electricity supplied to the grid. It was based on a previous study (Mayanti et al., 2021), which utilized data from a modular WtE plant manufacturer in Finland. Beylot et al. (2018) assumed bottom ash recovery, while this study assumed the bottom ash was landfilled. For the FW treated in AD, the environmental benefits were derived from avoided N-fertiliser production from digestate and petrol production from the upgraded biogas used in cars. The assumption was made based on the local AD that recovered digestate and upgraded the biogas into 97 % to fuel vehicles (Saarela, 2018; Stormossen, 2020). This study showed that the climate change impact of AD treating 1 t FW was around -220 kg CO₂ eq, while a comparable system from previous studies reported a value between -137 kg CO₂ eq and -333 kg CO₂ eq (Khoshnevisan et al., 2018; Tian et al., 2021).

4.3. LCA limitations and uncertainties

LCA study provides insights and benefits; however, it poses some limitations as well. Conducting LCA of FW is complex, and a lot of data is necessary. The data used in the LCA were average values, and assumptions were also applied. For example, agricultural production is a complex process where seasonality affects the amount of inputs (e.g., water, energy, or fertiliser), which affects the impacts. The average value was applied to simplify the study; hence, the LCA's outcomes must have also been affected. The port locations were assumed when the food was imported, and the transportation distance on land was also approximated. Another example could be found when calculating the impacts of the waste treatment process. Only a few areas or municipalities in Finland have data regarding the percentage of their FW treating in AD or WtE. Nonetheless, that information was averaged and assumed to represent how FW was treated nationally. The data regarding the Finnish food system was not always available; thus, data from different regions was applied.

Some measures were applied to deal with this issue. A priority tier was applied regarding data availability (the data reflects i) Finland, ii) Nordic, iii) Europe, or iv) other countries globally), and it was followed consistently throughout the study. When the LCA studies were available for Finland, instead of using the impacts quantified by the study, the inventories were used to build own LCA model to ensure consistency with the practitioner and the type of Ecoinvent data. A contribution analysis was conducted so that the hotspots could be identified. The magnitude of each contribution showed the importance of different processes or inputs so that focus could be given to improving data availability and quality of certain processes when doing it to all data was not possible. The choice of applying a consequential approach was also a measure to improve the LCA outcomes. Expanding boundaries means more data is required and increases uncertainties; however, it provides a more realistic picture of how connected things are. Applying scenario analysis was also important to explore different situations and investigate how the model behaved.

This study applied an optimisation problem that prioritised reducing waste of certain foods due to their high cost, environmental impact, or both. The algorithm favoured these foods because the reduction could lower climate change impacts and costs significantly compared to other foods. This study applied optimum optimisation rather than a real-world feasible reduction, which was deemed a limitation. It was applied because more information, such as consumer preferences or food supply availability, would be needed to represent a real-world feasible reduction. Nevertheless, the technique illustrated how MOO could be applied with LCA to address the FW problem; moreover, the model could be adjusted accordingly when new information is available.

4.4. Policy and managerial implications

Adopting upstream and downstream measures are important to reduce environmental impacts related to FW. The former deals with

preventing FW generation, while the latter refers to improving FW treatment. Some initiatives have been implemented in Finland to tackle the FW problem, such as setting a policy target to halve FW and recycle 65 % of FW, developing a FW monitoring system, campaigning to increase awareness, and developing a calculator to estimate FW generated from households (European Environment Agency, 2022; LUKE, 2022; Paulig Group, 2021). Price reduction by retailers is also a common practice applied to perishable food that is approaching the 'best-before' date; meanwhile, Fiksuruoka, a company that focuses on non-perishable food products, will purchase near the 'best-before' date products and resell them affordably (Sitra, 2021). The food sector also has signed a material efficiency commitment, resulting in a FW reduction of 427 t through improving production processes and reusing by-products (Motiva, 2023).

Nevertheless, more improvements can be made by any players in the supply chain. The optimisation results can be used as a guideline for prioritising the FW reduction. The food industry can switch to advanced packaging to extend shelf life or prevent premature food disposal. However, advanced packaging is expensive (Cheng et al., 2022), and swapping conventional packaging for advanced ones at once will be costly. Hence, gradual change in packaging can be implemented starting from highly prioritised food types shown by optimisation results. These advanced packaging can be active or intelligent (Thirupathi Vasuki et al., 2023). Active packaging integrates active substances in conventional packaging to maintain food quality and stability, so fresh plant products will last longer (Lehtonen et al., 2020). Intelligent packaging integrates advanced technology to detect changes in food quality and provide visual cues such as colour changes on the packaging as real-time information (Azeredo and Correa, 2021). Another strategy by the industry is using portion control packaging since families become smaller and the number of single households has increased. Food quality decreases rapidly once the packaging is opened, and smaller portion sizes can prevent spoilage (DistriFood, 2022). On the other hand, producing smaller portions of food can increase packaging waste; hence, improving packaging design and incorporating biodegradable materials are crucial.

The government can support other actors through economic instruments such as tax incentives and subsidies. For example, grants, tax deductions, or tax credits are available for businesses that apply food waste prevention technology such as advanced packaging. Tax incentives can be extended for food donations as well. In Finland, food can be donated by food business operators to food aid as long as the safety is not compromised (Finnish Food Authority, 2021). This measure can be supported by tax deductions or tax credits, as shown by other EU members such as Portugal, Italy, France, and Spain (European Commission, 2022b; Zuccarello, 2024). In Portugal, donors can get a tax deduction of up to 140 % of the value of the donated food, while in France, the donors can claim up to 60 % of the net value of donated food as a tax credit.

On the downstream stage, Finland has implemented a landfill tax for certain types of waste and a landfill ban for biowaste while mandating source-separated biowaste if the properties consist of at least five apartments (European Environment Agency, 2022). In 2024, the regulation mandates the sourced-separated biowaste for all residential properties in built-up areas with more than 10,000 inhabitants. Even in populated areas, the cost of sourced-separated biowaste collection and transportation is expensive (Mayanti and Helo, 2022); hence, more challenges are present in sparsely populated areas. To increase biowaste separation, the government can offer grants or subsidies via the municipality to support more establishment of decentralised biowaste processing facilities and home composting, especially in rural areas. Another strategy is to improve the pay-as-you-throw (PAYT) system. The current volume-based PAYT scheme, where residents are charged for waste disposal based on container volume and emptying frequency, is considered less effective. (European Environment Agency, 2022). Switching to weight-based PAYT can support waste reduction, a higher recycling rate, and more fair waste distribution among inhabitants

(Ukkonen and Sahmaa, 2021).

On the household level, meal planning plays a key role. It was reported that improper meal planning contributed significantly to households' FW generation (van Rooijen et al., 2024). The government and food industry can campaign for meal planning issues and provide a generic guideline on weekly meal planning based on household size, environmental impact, nutritional value, and costs. The meal planning app is also available at a relatively modest price, where users can outsource the trouble of planning the meal and listing the groceries. Users can choose the menu based on their diet preferences and the number of portions; the app generates a shopping list and recipe instructions for cooking (Sortedfood, 2022). Consumers shop only for ingredients needed and cook following the app's instructions.

Future research can focus on the role of packaging in reducing FW. It can highlight the potential savings of FW and the environmental impacts if active and intelligent packaging is used, including the possible trade-off between the price of conventional packaging and advanced packaging. Another avenue is to focus the study on the FW generated by retailers, the food industry, or food service to obtain different insights and apply different methods or scenarios.

5. Conclusions

This study investigated the impacts of household food waste (FW) in Finland, covering the edible fraction (EFW) and inedible one (IFW). The results indicate that the most significant environmental impacts are associated with the upstream stage during agricultural food production. Those impacts were associated with the EFW due to resources wasted for cultivation, processing, and transportation. Downstream waste treatment shows the importance of selecting effective options that promote sustainability while considering waste composition, infrastructure availability, and product substitution. Waste treatment results in benefits for climate change due to product substitution, although the benefits themselves are much less than the detrimental impact from the upstream stage.

The study's results should be used carefully in some other context due to the scope, boundaries, geographical location, assumption, and methods used in this study. Nevertheless, on a broad level, the significant impacts of agricultural production and some benefits from the downstream stage will still be applicable. Therefore, the study can be used as a guide to devise reduction strategies based on different types of waste, their cost, and their impacts. The focus should be on EFW prevention through different measures such as meal planning, packaging storage, portion control, and consumer education. The public should be more aware of the interconnectedness of the global food chain and take more deliberate action to reduce the EFW. The saying, 'The money is yours, but the resources belong to the society,' should remind us how we approach resource consumption, including food.

CRediT authorship contribution statement

Bening Mayanti: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2024.177438>.

Data availability

All the data are in the supplementary material

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