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Sustainability of food waste prevention through food consumption

Niina Sundin

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Niina Sundin

Faculty of Natural Resources and Agricultural Sciences

Department of Energy and Technology

Uppsala

SLU

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Cover: In the stomach, not in the bin
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Swedish University of Agricultural Sciences, Department of Energy and Technology, Uppsala, Sweden

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Errata for Sustainability of food waste prevention through food consumption

by Niina Sundin

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A calculation error was identified in the quantification of serving waste reduction using the plate waste tracker, affecting the associated environmental, social, and economic results. Below is a list of specific locations in the thesis where these errors occurred, along with the revisions, including some additional minor corrections. These adjustments do not alter the main findings or overall conclusions of the thesis, as the focus remains on plate waste prevention, but they ensure the accuracy of the reported data.

Page 54	Location: Figure 6. caption Is now: "…(sweets, snacks and fizzy drinks/soda)…" Should be: Remove the brackets and their contents.
Page 58	Location: line 28 Is now: "…24 E% of protein,…" Should be: "…24 E% of fat,…"
Page 61	Location: Figure 10. caption Is now: "Serving and plate waste levels…" Should be: "Plate waste levels…"
Page 61	Location: lines 5-10 Is now: "…reduction of 19 g (-37%) from the baseline of 52 g/guest in serving waste was also observed and again persisted in the long term (-16 g or -31%). Accounting for the reduction that was simultaneously observed in the control group (-6 g or -21%), the total reduction in serving waste was 13 g or 25%."

Should be: "…reduction of 7 g (-18%) from the baseline of 40 g/guest in serving waste was observed, persisting in the long term. Accounting for the reduction that was simultaneously observed in the control group (-6 g or -21%), the total reduction in serving waste was 1 g or 2%."

Page 63

Location: line 11
Is now: "…725 kg CO_2e per year and school."
Should be: "…56 kg CO_2e per year and school."

Page 64

Location: lines 5-6
Is now: "…3500 MJ of energy, 41 kg protein and 14 kg dietary fibre per school and year."
Should be: "…approximately 270 MJ of energy, 3 kg protein and 1 kg dietary fibre per school and year."

Location: lines 9-10
Is now: "The net economic benefits of the plate waste tracker amounted to 15,000 SEK (1300 EUR) per school and year."
Should be: "The net economic benefits of the plate waste tracker amounted to -7,000 SEK (-650 EUR) per school and year on a first-year basis."

Page 71

Location: line 3
Is now: "…serving waste decreased by 25%,…"
Should be: "…serving waste decreased by 2%,…"

Page 72

Location: lines 13-19
Is now: "The results also showed that the tracker generated a positive net economic benefit of 15,000 SEK per school annually, paying for itself in the first year. The whole sum would not be money in the pocket, since roughly one-third of the abated food waste would be eaten, and thus still produced, but the money would no longer be spent in vain. Conversely, the net benefit due to reduced serving waste, roughly two-thirds of the sum, could potentially be saved in production costs."

	Should be: "The net economic benefit of the tracker was negative in the first year but turned positive in the second year, amounting to 11,000 SEK annually thereafter. The whole sum would not be money in the pocket, since most of the abated food waste would likely be eaten, and thus still produced, but the money would no longer be spent in vain. Conversely, the net benefit due to reduced serving waste, roughly 17% of the sum, could potentially be saved in production costs."
Page 72	Location: lines 23-24
	Is now: "…a net benefit of roughly 48 MSEK (4 MEUR) saved in production costs in the first year,…"
	Should be: "… an annual net benefit of roughly 35 MSEK (3 MEUR) starting from the third year, after the investment is paid off,…"
	Location: lines 26-27
	Is now: "…3.5 million kg CO_2e, corresponding to approximately 2% of the total carbon footprint of Swedish school meals."
	Should be: "…1.1 million kg CO_2e, corresponding to approximately 1% of the total carbon footprint of Swedish school meals."
Paper VI	Location: Abstract
	Is now: "...reduced plate waste by 17% (4 g/guest) and serving waste by 50% (28 g/guest), indicating…"
	Should be: "…reduced plate waste by 17% (4 g/guest), indicating…"
	Is now: "…environmental impacts (1697 kg CO_2e per school and year and nutrient losses (8571 MJ energy per school per year), while generating economic cost savings of 40,925 SEK (3600 EUR) per school per year in addition to paying back its investment cost after the first year."
	Should be: "…environmental impacts (by 212 kg CO_2e per school & year) and nutrient losses (1018 MJ, per school & year), while proving cost-effective with a payback period of only 2 years."

Paper VI

Location: 3.1.1 Plate waste tracker

Is now: "In comparison to baseline of 56 g/guest, a reduction of 61% was observed at intervention quantification (22 g/guest) and a reduction of 85% at post-intervention (8 g/guest)."

Should be: "In comparison with the baseline of 40 g/guest, a reduction of 6 g/guest (16%) was observed in the intervention quantification (34 g/guest) and a reduction of 7 g/guest (18%) in the post-intervention quantification (33 g/guest)."

Is now: "Taking the reductions in the control group…remaining in the long term."

Should be: The entire sentence should be removed.

Location: Figure 4.

Is now: Plate waste tracker; serving waste; baseline=56 g/guest; intervention=22 g/guest; post-intervention quantification=8 g/guest

Should be: baseline=40 g/guest; intervention=34 g/guest; post-intervention quantification=33 g/guest

Location: Table 3. caption

Is now: "…corresponding to reduced serving and plate waste…"

Should be: "…corresponding to reduced plate waste…"

Location: Table 3.

Should be: Replace Table 3. with the following table:

prevented plate waste (kg/school and year)	212
Environmental impact savings	
Carbon footprint (CO_2e/school and year)	212
*Corresponding number of school meals**	*255*
Social impact savings	
Energy (MJ/school and year)	1018
*Corresponding number of school meals***	*339*
Dietary fibre (g/school and year)	4031
*Corresponding number of school meals***	*538*
Protein (g/school and year)	12094
*Corresponding number of school meals***	*920*
Economic impact savings	
Benefits (abated plate waste, SEK (EUR)/school and year)***	7002 (620)
Costs (plate waste tracker, SEK (EUR)/school)	18000 (1600)
Net benefits SEK (EUR)	-10998 (-980)
Corresponding number of school meals	*-289*

*based on carbon footprint of 0.83 kg CO2e/meal (Eustachio Colombo et al., 2020)

**number of school meals fulfilling 30% of the daily energy (10 MJ), fiber (25 g), and protein (44 g) requirement of schoolchildren (averaged for 7-16 of age).

***based on 4 g/guest plate waste reduction, 298 guests/day, 178 school days/year, and cost of 33 SEK/kg plate waste

Location: 3.2.1 Environmental impact

Is now: "The climate mitigation impact corresponding to the serving waste reduction of 28 g/guest…."

Should be: The whole sentence to be removed

Paper VI	Is now: “The abated environmental impact from reduced plate waste corresponded to the CO_2e of 255 school meals, and from reduced serving waste to 1789 school meals.”

Should be: “The abated environmental impact from reduced plate waste corresponded to the CO_2e of 255 school meals.”

Location: 3.2.2 Social impact

Is now: “The abated nutrient losses due to reduced plate waste…”

Should be: “The abated nutrient losses due to reduced plate waste tracker amounted to approximately 1000 MJ of energy, 12 kg protein, and 4 kg dietary fiber per school and year.”

Is now: “The abated nutrient losses due to reduced serving waste…”

Should be: The entire sentence should be removed.

Is now: “In total, the nutrient savings from plate waste and serving waste corresponded to…needs of pupils.”

Should be: “These nutrient savings corresponded to 339, 920, and 538 school meals, respectively, based on fulfilling 30% of the respective daily nutrition needs of pupils.”

Location: 3.2.3 Economic impact

Is now: “The net economic benefits of the plate waste tracker used in public schools in Sweden amounted to approximately 41,000 SEK (3400 EUR) per school and year giving a cost-benefit ratio of 1:3. The total savings from plate and serving waste corresponded to the cost of 1077 school meals.“

Should be: ”The net benefit of the PWT over all participating schools was -11,000 SEK (-970 EUR) per school, so the investment costs were recouped and positive net benefits were generated during the third year of use.”

Location: 4. Discussion, 1st paragraph

Is now: “Similar to the findings by Malefors et al.(2022b), it also had the unintentional spillover effect of reducing serving waste by 50%...”

Should be: The entire sentence should be removed.

Paper VI Is now: "Furthermore, in addition to mitigating…"

Should be: "In addition to mitigating environmental impacts by 212 kg CO_2e per school and year, the PWT also saved valuable nutrients, such as protein (12 kg per school and year) and fiber (4 kg per school and year)."

Location. 4. Discussion, 2nd paragraph

Is now: "From the cost point of view, the plate waste tracker had the advantage of paying itself back and generating cost savings already during its first year of use."

Should be: "The PWT proved to be cost-effective, paying for itself by the third year after installation."

Is now: "Furthermore, the plate waste tracker had the benefit of reducing both plate waste and serving waste tackling two problem areas through one measure."

Should be: "The results indicated a potential dual benefit, in reducing both plate and serving waste, as also found by Malefors et al. (2022b), addressing two issues with one measure, although this is yet to be confirmed and requires future study."

Location. 4. Discussion, 3rd paragraph

Is now: "However, the spillover effect can also be a welcomed effect…although targeting plate waste."

Should be: "However, spillover effects could also be beneficial as suggested by the present results, where PWT appeared to have a potential waste-reducing effect on serving waste."

Is now: "…the baseline for plate waste was 23 g/guest, and for serving waste, 56 g/guest."

Should be: "…the baseline for plate waste was 23 g/guest, and for serving waste, 40 g/guest."

Is now: "This indicated that although plate waste was…by reducing plate waste."

Should be: "This indicates that while plate waste was at a relatively low level, there was still significant plate waste prevention potential and associated cost, nutrient, and environmental savings."

Paper VI Location: Conclusions

Is now: "The plate waste tracker significantly reduced plate waste by 17% and serving waste by 50%, mitigating environmental impacts (1697 kg CO_2e per school and year), and nutrient losses (8571 MJ energy per school and year)."

Should be: "The PWT significantly reduced plate waste (by 17%), mitigating environmental impacts (by 212 kg CO_2e per school and year) and losses of nutrients such as protein (12 kg per school and year) and fiber (4 kg per school and year)."

Is now: "In addition, the waste tracker generated cost savings amounting to 40,925 SEK per school and year after the first year of use, in addition to paying back its investment cost."

Should be: "In addition, PWT proved highly cost-efficient, with a payback period of only 2 years."

Sustainability of food waste prevention through food consumption

Abstract

Food is wasted in unacceptable amounts and an epidemic of overeating is sweeping the world, while billions of people suffer from food insecurity. In Sweden, retailers waste around 89,000 tons and public caterers 37,000 tons annually, comprising mostly edible food. Halving food waste at the consumption level faces challenges due to complex root causes. A stronger focus on food waste prevention is needed, but existing measures lack empirical evidence of their reduction potential and sustainability impacts. These gaps were addressed in this thesis by assessing two reduction measures, surplus food redistribution and plate waste prevention in school meals. Using diverse methods, such as surveys, life cycle assessment, material flow analysis and nutritional calculations, the food waste reduction potential and environmental, economic and social impacts of the measures were evaluated. The magnitude and climate impact of food overconsumption, *i.e.* metabolic food waste, was also analysed. The results revealed high environmental impact of overeating, corresponding to up to 10% of food-related climate impact in Sweden. The redistribution system proved effective, with approximately 78% of donated food eaten. Donations also outcompeted anaerobic digestion in environmental impact mitigation despite substantial rebound effects, while adding social stakeholder value. Educational approaches, including plate waste tracker and serving popular instead of unpopular school meals, showed great long-term reduction potential for plate waste (~19%). Overall, the results indicated high importance of limiting food overconsumption from both a health and environmental perspective and showed that redirecting edible food waste to people can protect the environment and provide valuable nutrients, accruing potential health benefits.

Keywords: food systems, surplus food redistribution, public catering, school meals, metabolic food waste, life cycle assessment, climate impact, sustainable nutrition

Hållbarheten av att förebygga matsvinn genom matkonsumtion

Sammanfattning

Oacceptabelt mycket mat slängs i onödan och miljarder människor lider av osäker en osäker tillgång på livsmedel, samtidigt som en epidemi av överätande sveper över världen. I Sverige slänger detaljhandeln cirka 89 000 ton och offentliga storkök 37 000 ton mat årligen, vilket till största delen består av ätbar mat. Att halvera matsvinnet på konsumtionsnivå är utmanande på grund av komplexa grundorsaker. Ett starkare fokus på att förebygga matsvinn behövs, men det saknas tillräcklig kunskap om minskningspotential och hållbarhet för befintliga åtgärder. Dessa kunskapsluckor undersöktes genom att utvärdera två åtgärder, donation av överskottsmat från butiker samt förebyggande av tallrikssvinn i skolor. Genom olika metoder, såsom intervjuer, livscykelanalys, materialflödesanalys och näringsberäkningar, bedömdes hur mycket matsvinnet minskar samt miljömässiga, ekonomiska och sociala effekter av åtgärderna. Dessutom granskades omfattningen och klimatpåverkan från överkonsumtion av mat, så kallat metaboliskt matsvinn. Resultaten visade att miljöpåverkan från överkonsumtion av mat motsvarade upp till 10% av matens klimatpåverkan i Sverige. Matdonationer visade på hög effektivitet då cirka 78% av den donerade maten blev uppäten av behövande människor. Donationer överträffade också biogasproduktion när det gäller att minska miljöpåverkan trots betydande rekyleffekter, samtidigt som de skapade sociala värden för olika intressenter. Pedagogiska metoder såsom tallrikssvinnsvåg och servering av populära skolmåltider istället för impopulära visade en hög potential för en bibehållen minskning av tallrikssvinnet (~19%). Sammantaget visade resultaten att det är nödvändigt att begränsa överätandet, inte bara ur ett hälsoperspektiv utan även ur ett miljöperspektiv, medan omfördelning av ätbar överskottsmat till människor inte bara bevarar miljön utan även näringsämnen i maten som har potential att ge värdefulla hälsofördelar.

Nyckelord: livsmedelssystem, donation av överskottsmat, offentliga måltider, skolmåltid, metaboliskt matavfall, livscykelanalys, klimatpåverkan, hållbar nutrition

Ruokahävikin ehkäisemisen kestävyys ruokaa kuluttamalla

Tiivistelmä

Ruokahävikkiä syntyy kohtuuttomia määriä ja maailmassa vallitsee ylensyönnin epidemia samalla kun miljardit ihmiset kärsivät nälästä ja ruokaturvattomuudesta. Ruotsissa vähittäiskauppojen hävikki on vuosittain noin 89,000 tonnia sekä julkisten ruokapalveluiden 37,000 tonnia koostuen pääosin syömäkelpoisesta ruoasta. Ruokahävikin vähentäminen on haastavaa, johtuen hävikin monimutkaisista juurisyistä. Ruokahävikin ehkäisyyn tulisikin keskittyä entistä enemmän, mutta näyttö ehkäisevien toimenpiteiden vähentämispotentiaalista ja kestävyysvaikutuksista on puutteellista. Näihin puutteisiin pyrittiin vastaamaan arvioimalla kahta ehkäisemistoimenpidettä Ruotsissa, joihin kuuluivat ruokalahjoitustoiminta ja lautasjätteen synnyn ehkäiseminen kouluruokaloissa. Tutkimuksessa käytettiin erilaisia menetelmiä, kuten kyselyitä, elinkaari-arviointia, materiaalivirta-analyysiä ja ravintoarvolaskelmia ruokahävikin vähentämispotentiaalin sekä ympäristö-, taloudellisten ja sosiaalisten vaikutusten arvioimiseen. Lisäksi tarkasteltiin ruotsalaisten aikuisten ylensyönnin, *metabolisen ruokahävikin*, määrää ja ilmastokustannuksia. Tulokset paljastivat ylensyönnin korkeat ilmastokustannukset vastaten jopa 10%:a ruokaan liittyvistä ilmastovaikutuksista Ruotsissa. Ruokalahjoitustoiminta oli tehokasta, sillä noin 78% lahjoitetusta ruoasta syötiin. Ruokalahjoitukset päihittivät myös anaerobisen mädätyksen (biokaasu tuotannon) positiivisten ympäristövaikutusten kannalta huomattavista ”rebound”-vaikutuksista huolimatta, ja tarjoten samalla sosiaalista lisäarvoa sidosryhmille. Suosittujen kouluaterioiden tarjoaminen epäsuosittujen sijaan sekä pedagogiset lähestymistavat, kuten lautasjätteen seuranta vähensivät lautasjätteen määrä pitkällä aikavälillä huomattavasti (~19%). Kaiken kaikkiaan tulokset viittasivat siihen, että ruoan liikakulutusta tulisi rajoittaa paitsi terveyden myös ympäristön kannalta, kun taas syömäkelpoisen ruokahävikin syöminen ei pelkästään säästänyt ympäristöä vaan myös arvokkaita ravintoaineita luoden mahdollisia terveyshyötyjä.

Avainsanat: elintarvikejärjestelmä, ruoka-apu, julkiset ruokapalvelut, kouluruoka, metabolinen hävikki, elinkaariarviointi, ilmastovaikutukset, kestävä ravitsemus

Preface

“Vision without action is a daydream.
Action without vision is a nightmare.”

-Japanese proverb

Dedication

To Anders, for being my rock,
and for showing me that *doing* is the best practice.

Contents

List of publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I. Sundin, N., Rosell, M., Eriksson, M., Jensen, C. & Bianchi, M. (2021). The climate impact of excess food intake - An avoidable environmental burden. *Resources, Conservation and Recycling* 174:105777. doi:10.1016/j.resconrec.2021.105777

II. Sundin, N., Persson Osowski, C., Strid, I. & Eriksson, M. (2022). Surplus food donation: Effectiveness, carbon footprint, and rebound effect. *Resources, Conservation and Recycling* 181:106271. doi:10.1016/j.resconrec.2022.106271

III. Sundin, N., Bartek, L., Persson Osowski, C., Strid, I. & Eriksson, M. (2023). Sustainability assessment of surplus food donation: A transfer system generating environmental, economic, and social values. *Sustainable Production and Consumption* 38: 41–54. doi:10.1016/j.spc.2023.03.022

IV. Sundin, N., Malefors, C., Danielsson, M., Hardiyanti, M., Persson Osowski, C. & Eriksson, M. (2023). Investigating goal conflicts in menu planning in Swedish school catering on the pathway to sustainable development. *Resources, Conservation and Recycling* 190:106822. doi:10.1016/j.resconrec.2022.106822

V. Sundin, N., Halvarsson, R., Scherhaufer, S., Schneider, S. & Eriksson, M. (2024). From plate to waste: Composition of school meal waste and associated carbon footprint and nutrient loss. *Resources, Conservation and Recycling* 206, 107656. doi:10.1016/j.resconrec.2024.107656

VI. Sundin, N., Malefors, C., Strotmann, C., Orth, D., Kaltenbrunner, K., Obersteiner, G., Scherhaufer, S., K., Sjölund, A., Persson Osowski, C., Strid, I. & Eriksson, M. (2024). Sustainability assessment of educational approaches as food waste prevention measures in school catering (submitted).

The contribution of Niina Sundin to the papers included in this thesis was as follows:

I. Planned the paper together with the co-authors. Performed the data collection, calculations and analysis. Wrote the paper in cooperation with the co-authors.

II. Planned the paper in cooperation with the co-authors. Performed and/or supervised the data collection, and conducted the calculations and analysis. Wrote the paper with support from the co-authors.

III. Planned the paper in cooperation with the co-authors. Performed and/or supervised the data collection. Conducted the life cycle assessment with support from the co-authors. Conducted other calculations and analysis. Wrote the paper with support from the co-authors.

IV. Planned the paper in cooperation with the co-authors. Supervised the data collection and calculations. Analysed the results and wrote the paper together with the co-authors.

V. Planned the paper with input from the co-authors. Supervised and conducted the data collection and carbon footprint calculations. Conducted the nutrient calculations and analysis. Wrote the paper with input from the co-authors.

VI. Planned the paper with input from the co-authors. Performed the data collection with support from the co-authors. Conducted the calculations and analysis. Wrote the paper with input from the co-authors.

Papers produced but not included in the present thesis:

VII. Bartek, L., **Sundin, N**., Strid, I., Andersson, M., Hansson, P.-A. & Eriksson, M. (2022). Environmental benefits of circular food systems: The case of upcycled protein recovered using genome edited potato. *Journal of Cleaner Production* 380, 134887. https://doi.org/10.1016/j.jclepro.2022.134887

VIII. Malefors, C., **Sundin, N**., Tromp, M. & Eriksson, M. (2022). Testing interventions to reduce food waste in school catering. *Resources, Conservation and Recycling* 177, 105997. https://doi.org/10.1016/j.resconrec.2021.105997

IX. Persson Osowski, C., Osowski, D., Johansson, K., **Sundin, N**., Malefors, C. & Eriksson, M. (2022). From old habits to new routines—a case study of food waste generation and reduction in four Swedish schools. *Resources* 11 (1), 5. https://doi.org/10.3390/resources11010005

Abbreviations

CO_2e	Carbon dioxide equivalents
E%	Energy percent
EU	European Union
EC	European Commission
FAO	Food and Agricultural Organisation of the United Nations
GHGE	Greenhouse gas emissions
GWP	Global warming potential
LCA	Life cycle assessment
MFA	Material flow analysis
MFW	Metabolic food waste
NNR	Nordic Nutrition Recommendations
SDG	Sustainable development goal
S-LCA	Social life cycle assessment
UN	United Nations
WHO	World Health Organization of the United Nations
WND	Wasted nutrient days

1. Introduction

Wasting edible food increases the stress on an overburdened Earth system (Springmann *et al*., 2018). Six of the nine planetary boundaries have already been transgressed and modern food systems are a significant driver of this problem (Richardson *et al*., 2023). Food systems demand extensive resources, such as energy, water and land, and are major polluters, contributing to eutrophication and to approximately one-third of total global greenhouse gas emissions (GHGE) (Bonsdorff, 2021; Crippa *et al*., 2021). In addition to the devastating impacts on climate, there is ample evidence of negative impacts of current food systems on biodiversity, human health and social justice (IPBES, 2019). While billions of people continue to suffer from hunger and food insecurity, *i.e.* lack regular access to sufficient food, vast amounts of food are overconsumed, contributing to an epidemic of overweight and obesity and to over one-third of all food produced globally being lost or wasted (UNEP 2021; WHO 2021b; FAO 2023b). Thus, alleviating the pressure on food systems through prevention of food waste emerges as a compelling and highly prudent action.

Despite the progress made in understanding the food waste issue and the global agreement on halving food waste and reducing food losses by 2030, reducing food waste remains challenging (UN, 2024a). An advocated policy concept, the waste hierarchy, provides a clear priority list for the prevention and management of food waste. It places prevention at the top, followed by re-use for human consumption, such as surplus food redistribution, while incineration and landfilling are at the bottom (EC, 2020a). However, staggering quantities of food continue to be wasted, with an estimated 931 million tonnes of food wasted globally at the consumption stage (UN, 2024a). An unacceptable amount of food is also wasted in Sweden, estimated at 1.4 million tonnes, with retailers generating 89,000 tonnes and catering establishments 37,000 tonnes in 2022 (Hultén *et al*., 2024). While retail and catering are not the largest contributors, their food waste comprises mostly edible food that has undergone resource-intensive processes, entailing an unnecessary environmental burden. This food waste is mostly treated by less preferred options in the waste hierarchy, such as incineration and anaerobic digestion in Sweden, or dumping or landfill in the global context, highlighting a large gap between policy and practice (Sabour *et al*., 2020; Johansson, 2021; Sörme *et al*., 2021).

The multifaceted nature of the root causes complicates the search for straightforward solutions to food waste. For example, food waste is embedded in food supply chains, generating so-called systemic surplus food (Messner *et al*., 2020). A lack of financial instruments discourages stakeholders, such as retailers, from curbing food waste, maintaining the *status quo* (Mourad, 2016; Rosenlund *et al*., 2020). Disparities in the valuation of food, where prices fail to reflect true costs, contribute to wastage, together with factors such as price, while awareness, cultural norms and personal preferences regarding food safety and taste influence consumer behaviours (FAO, 2013; Schanes *et al*., 2018). In countries such as Sweden, successful transition from landfilling to incineration and toward anaerobic digestion may mistakenly indicate an ambition to reduce food waste, but fails to address its root causes. This complexity means that no single policy can fully resolve the food waste problem and that multiple policy actions must be devised and implemented within a broader food systems framework (Reynolds, 2022).

Policy actions across the waste hierarchy are likely needed to tackle the food waste issue, but more action on food waste prevention in particular is required (De Laurentiis *et al*., 2020). Comprehensive knowledge is essential to reveal the sustainability outcomes of food waste prevention and management options, but practical evidence on the reduction potential and sustainability impacts of the top-priority options is currently insufficient (Reynolds *et al*., 2019; De Laurentiis *et al*., 2020). Previous research has focused on assessing lower waste management options in terms of their environmental impacts alone (Caldeira *et al*., 2019). However, addressing fundamental social sustainability challenges, such as poverty and inequity, is a prerequisite to solving other issues, such as climate change (UN, 2015b). This means that a holistic approach integrating various evaluation frameworks is necessary to prioritise various policy options effectively (Goossens *et al*., 2019).

These knowledge gaps were addressed in this thesis by assessing the sustainability impacts of food waste reduction measures at the highest level of the waste hierarchy, *i.e*. prioritising food consumption over food waste. The measures investigated, both in Sweden, were surplus food redistribution and plate waste prevention in school canteens. The climate impact of food overconsumption was also scrutinised, since food consumption beyond human energy needs contributes to overweight and obesity and is akin to food waste, although mostly overlooked as such. While it is evident that the issue of food waste cannot be solved merely by consuming all food that would otherwise be wasted, this thesis examined whether redirecting food to people, rather than waste bins, offers significant sustainability gains with potentially far-reaching benefits.

2. Aim, objectives and structure of the thesis

2.1 Aim and objectives

The overarching aim of the work in this thesis was to determine the connection between food waste and food consumption, in order to mitigate food waste through increased or decreased food intake in Sweden, and thereby foster more sustainable food systems. Specific objectives were to:

- Quantify food overconsumption among Swedish adults and assess its climate impact (Paper I).
- Investigate the food waste reduction potential of surplus food redistribution and assess its environmental, economic and social impacts, including rebound effects (Papers II-III).
- Demonstrate plate waste prevention measures in school catering, including educational approaches and meal planning, to evaluate their potential to reduce food waste. (Papers IV & VI).
- Assess the environmental, economic and social impacts of plate waste prevention in school catering (Papers V & VI).

2.2 Structure of the thesis

The objectives of the thesis were fulfilled by work presented in Papers I-VI, which was divided into three theme areas: *food overconsumption* (Paper I), *surplus food donation* (Papers II & III), and *plate waste prevention* (Papers IV-VI) (Figure 1). The *food overconsumption* theme focused on the climate cost of hidden food wastage in Sweden caused by the adult population consuming food above the energy needs of their bodies. In this context, consumed food can be considered waste, also referred to as *metabolic food waste* (MFW) (Serafini & Toti, 2016). In contrast, in the *surplus food donation* and *plate waste prevention* themes, food waste could potentially be reduced through food consumption, *i.e.* eating food that would otherwise be wasted. In this context, potential sustainability gains and trade-offs of reducing food waste through donations to people in need, and through plate waste prevention measures in school canteens in Sweden, were investigated.

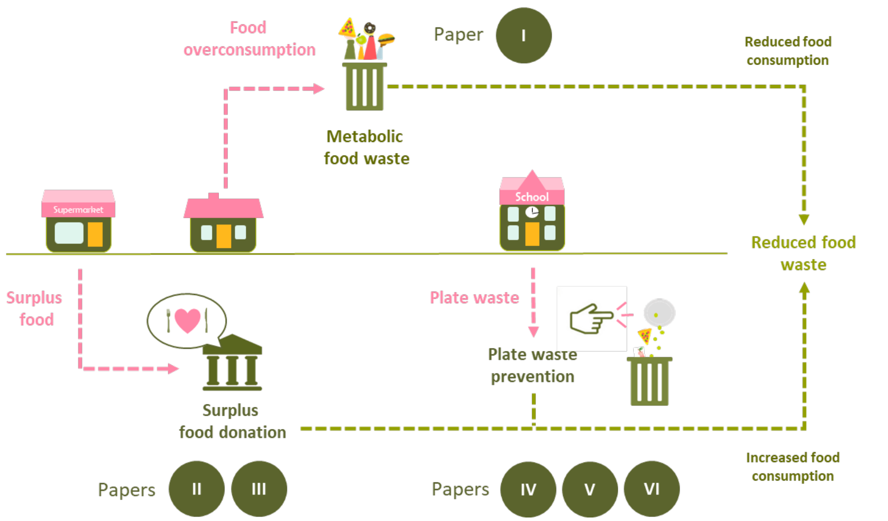

Figure 1. Structure of the work in this thesis, which was divided into three theme areas: *food overconsumption*, *surplus food donation* and *plate waste prevention*, and the corresponding papers. The *food overconsumption* theme considered overeating food to be food waste, whereas the other two themes investigated measures where food waste could be prevented by consuming food.

3. Background

The world faces multiple global challenges that urgently need solving and which are well reflected in the 17 Sustainable Development Goals (SDGs) of the United Nations (UN) (2015a). These goals were developed to ensure peace and prosperity for people and the planet both now and in the future. None of these goals can be solved in isolation, as they are all interconnected, and solving them requires transdisciplinary research and multi-actor approaches at all levels of society. Although all 17 SDGs are important to secure a sustainable future, SDG 13, on climate action, is often considered to be in most urgent need of being tackled.

At the recent UN Climate Change Conference (COP 28), global consensus to transition away from fossil fuels was reached, along with agreements to triple renewables, ensure climate justice and increase resilience (UN, 2024b). While some considered this remarkable, many stakeholders wanted more ambitious goals. Scientists point out that the pace of action is critical, as we are currently on track for almost 3 ºC of warming instead of the 1.5 ºC target set in the 2015 Paris Agreement (UNEP, 2023). Achieving the 1.5 ºC goal requires a full fossil fuel phase-out, massive investments in nature and carbon removal, but also transforming the global food system (Future Earth, 2023). The FAO roadmap includes a 50% reduction in global food waste by 2030 and incorporating all remaining food loss into a circular bioeconomy by 2050 as key milestones (FAO, 2023a).

The European Union (EU) is striving for climate neutrality and sustainability, acknowledging that driving such transition requires balancing environmental, social and economic aspects for long-term success (EC, 2023). In the EU sustainability transition strategy, sustainable production and consumption is highlighted as one of the key areas and is also included as a target in SDG 12. The EU has pledged to reduce per capita food waste at retail and consumer level by 50% by 2030, in accordance with target 12.3 of SDG 12 (EU, 2023). To achieve this, national targets should aim for a 10% reduction in the food industry and a 30% decrease per capita at consumer level by 2030. The current target in Sweden is to reduce the total amount of food waste by at least 20% per capita by 2025, while also ensuring that a larger proportion of food produced reaches retailers and consumers (EC, 2024).

The focus in this thesis was on SDGs 2, 12 and 13, *i.e.* zero hunger, responsible consumption and production, and climate action, and especially target 12.3, *i.e.* to halve global per capita food waste. The work was also intertwined with goals such as no poverty (SDG 1) and good health and well-being (SDG 3), which are often considered prerequisites for achieving other SDGs such as 2, 12 and 13.

3.1 The issue of food waste

Food has been wasted throughout human history, but for different reasons than today. Historically, the reasons behind food wastage were often beyond human control, such as bad weather or lack of infrastructure and technology to preserve food, but today food wastage is often caused by lack of awareness, over-purchasing, lack of planning or strict cosmetic standards, *i.e.* factors which are within human control (Schneider, 2013).

Food waste is a global issue, occurring from farm to fork including all stages of the food supply chain. According to recent estimates, up to 40% of all food produced is lost or wasted (WWF, 2021). Food that is not consumed is associated with approximately 10% of global greenhouse gas emissions, in addition to an astounding annual cost of one trillion USD (UNEP, 2024). Moreover, a substantial variety and amount of nutrients are lost globally due to high waste of perishable, nutrient-dense foods such as fruit and vegetables (Chen *et al.*, 2020). The largest share of food waste occurs at the consumption stage. This totalled 931 million tonnes in 2019, of which 61% was generated by households, 26% by food services and 13% by retail (UNEP, 2021).

In the EU, 58.4 million tonnes (or 131 kg/person/year) of food waste are generated annually, with devastating costs (Eurostat, 2023a). This wastage represents 254 million tonnes of carbon dioxide-equivalents (CO_2e) (16% of EU food system climate impact), 132 billion EUR in economic losses and

9.3 billion EUR cost in treating the waste. While this wastage is occurring, 37 million people are food insecure, *i.e*. they cannot afford a meal containing meat, fish or a vegetarian equivalent every second day (Eurostat, 2023a).

Reducing food waste carries a multitude of potential benefits. For example, it helps in curbing environmental impacts and addressing climate change substantially, enhances food and nutrition security, contributes to food affordability, and accrues financial savings for households (De Jong *et al*., 2023). However, this potential has previously been largely overlooked, possibly due to lack of understanding of the true scale of food waste and its impacts (UNEP, 2021). In response to these challenges, initiatives such as the Farm to Fork Strategy embedded in the European Green Deal are crucial. That strategy aims to significantly reduce the environmental and climate footprint of the EU food system while also targeting the pressing issue of food waste (EC, 2020a).

3.2 Food waste definitions

Clear and unambiguous definitions of food waste are essential for designing and evaluating prevention measures and policies. However, creating universally accepted definitions is challenging, due to the complex nature of the food supply chain and differing stakeholder perspectives. Different regions also vary in terms of cultural norms and consumer behaviours, influencing what is considered waste. For example, items such as banana peels and chicken feet may be regarded as inedible in some regions, but not in others.

However, it is important to ensure that the much-needed discussion on common definitions does not divert attention and delay action on food waste prevention. It is crucial to balance the need to harmonise definitions against the need to implement food waste prevention measures based on the current level of knowledge. Immediate action is urgently needed due to the food waste crisis, even as long-term efforts to harmonise definitions continue. Meanwhile, transparency of the food waste definitions used is necessary. This thesis applies the EU definition, where food waste is considered all food that is discarded, including its associated inedible parts (*e.g*. bones or fruit cores) (EC, 2020a). Other food waste definitions relevant to the work in this thesis are presented in Table 1.

Table 1. *Definitions of food waste-related terms relevant to the work presented in this thesis*

Theme	Term	Definition
Food over-consumption	Metabolic food waste (MFW)	MFW is defined by Serafini & Toti (2016) as “Food eaten above physiological needs, manifesting as obesity”. In this thesis, MFW encompasses food overconsumption due to overweight and obesity, defined in turn according to the body mass index cut-offs set by WHO (2024).
Surplus food donation	Surplus food	Safe and edible food available for donation from *e.g.* retail that could not be sold and would have otherwise been wasted (EC, 2017).
	Edible food waste	Parts of food intended to be ingested (EC, 2019).
	Inedible food waste	Parts of food not intended to be ingested, such as bones (EC, 2019), and peels and trimmings of fruit and vegetables (De Laurentis *et al*., 2018).
Plate waste prevention	Plate waste	“All waste from the plates of guests. May contain inedible parts, such as bones and peels.” (Malefors, 2022). Plate waste is mostly edible food waste.
	Serving waste	“Food served that did not reach the plates of guests.” (Malefors, 2022). Serving waste is mostly edible food waste.

3.3 The food waste hierarchy

The waste hierarchy has been part of EU policy since the 1970s (EC, 2008). A few decades later the *food waste hierarchy* was derived, to identify and prioritise the best measures to prevent and manage food waste, taking environmental, social and economic sustainability perspectives into account, although studies confirming these were yet to come (EC, 2020a). The highest priority in the food waste hierarchy is prevention, followed by redistribution of surplus food (Figure 2). Since its introduction, various policymakers around the world have adopted the framework. However, different regions have interpreted the measures slightly differently. The United Kingdom includes surplus food redistribution and animal feed under food waste prevention (Defra, 2024), while the United States and EU consider these as food waste reduction measures (EC, 2020a; US EPA, 2023). Nevertheless, these food waste hierarchies agree that the top priority is prevention, followed by surplus food redistribution and other re-use, as these measures are the most environmentally preferable pathways due to displacing additional food production (US EPA, 2023).

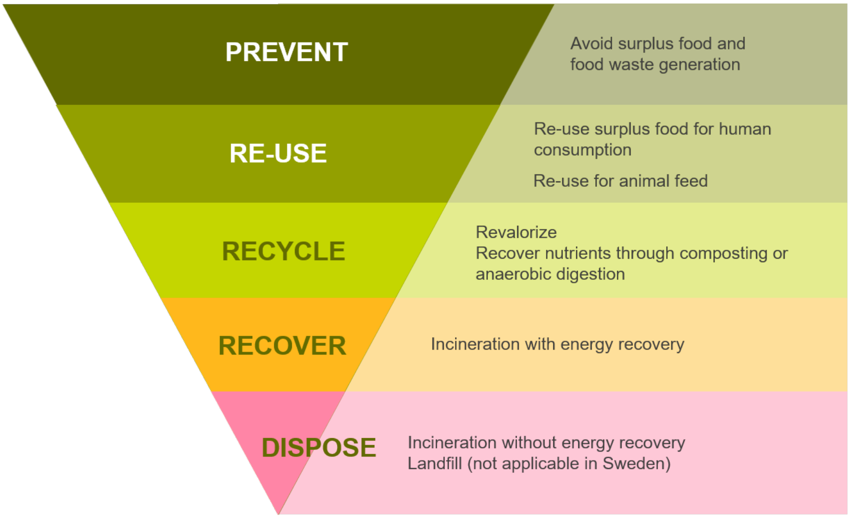

Figure 2. The food waste hierarchy, listing the most preferable option at the top and down to the least preferable options for food waste prevention and management. Adapted from EC (2020a).

3.4 Hunger and food insecurity

Globally, it is projected that almost 600 million people will suffer from hunger by 2030, when the world should instead have reached the SDG on zero hunger (FAO, 2023b). The current prevalence of undernourishment is still above pre-Covid-19 pandemic levels, as the world continues to be shaken by conflicts, climate extremes, economic shocks and increasing food prices. As a result, approximately 30% of the global population suffered from food insecurity in 2022, where continuous access to essential food in terms of quantity and quality could not be guaranteed, and 42% could not afford a healthy diet in 2021 (UNEP, 2024).

Although food insecurity is mostly associated with low-income countries, it is also a devastating issue in high-income regions (Pollard & Booth, 2019). The recent rise in the cost of living has resulted in 8.3% of the European population living in food insecurity (Eurostat, 2023b). Data on food insecurity in Sweden are limited, but 5.4% of the population were reported to experience moderate to severe food insecurity in 2021, with an increasing trend (FAO, 2024). In addition, a major increase in demand for food donations has been reported in Sweden and, in response, new charity units have started operating, suggesting that the prevalence of food insecurity may be growing (Minorsson, 2022; Siltberg, 2022).

3.5 Food donation landscape in the EU and Sweden

As a response to tackle food insecurity and the food waste issue simultaneously, surplus food redistribution has become an advocated policy measure in many high-income countries. The EU has taken significant steps to encourage food donation and food waste reduction, by setting food waste reduction targets and by creating guidelines and frameworks to incentivise and support food donation (De Laurentiis *et al*., 2023). The EU food donation guidelines were adopted in 2017 to clarify stakeholder compliance with the EU regulatory framework regarding food safety & hygiene, traceability, liability and value-added tax (EC, 2017).

However, the maturity level of the surplus food redistribution system varies greatly between EU Member States (EU, 2019). The more advanced countries such as France, Italy, Estonia and the Netherlands, have implemented a high number of measures deemed necessary to successfully facilitate food donations. For example, France, Italy, the Netherlands and also the UK have adopted the food waste hierarchy in their national laws, promoting redistribution over any other food waste pathway. France and Italy are also recognised for their progressive food donation laws, with France passing legislation requiring supermarkets to donate unsold food to charities and Italy passing the "Good Samaritan Law" simplifying the process of food donations by providing tax incentives and reducing legal barriers for donors (Condamine, 2020a, 2020b).

Food waste reduction through surplus food donations in Sweden began in the early 2000s, with significant growth since 2015 due to the launch of the SDGs and the refugee crisis (Berglund & Kristjansdottir, 2024). Social trends such as increasing income inequality, rising food prices and inflation have heightened the need for donations in recent years (SCB, 2023). Meanwhile, there is growing interest in reducing food waste, and together these have contributed to an significant increase in donations and in the organisations that redistribute food (Berglund & Kristjansdottir, 2024). Recently, the Swedish authorities have also supported redistribution efforts by *e.g.* removing VAT on donated foods near their expiry date in 2022 and by publishing donation guidelines in 2024 (IVL, 2024; Swedish Food Agency, 2022). Currently, approximately 9500 tons of food are redistributed annually, which is more than double the 2021 figure of 4500 tons but still corresponds to only 9% of total retail and wholesale food waste (Hultén et al., 2024). The latest waste regulation, which came into force in early 2024, requires packaging to be separated from biological waste before disposal, which may provide an incentive for retailers to further increase their surplus donations (Berglund & Kristjansdottir, 2024).

3.6 The epidemic of obesity

The failure of modern food systems to provide adequate nutrition has manifested itself in widespread malnutrition globally (WHO, 2021a). Around 800 million people world-wide suffer from undernourishment, while two billion people battle overweight or obesity, a concern now prevalent in both high- and low-income countries, especially in urban areas (WHO, 2021a, 2021b). Over the past four decades, adult obesity rates have nearly tripled worldwide, and childhood overweight and obesity have risen dramatically (Di Cesare *et al.*, 2019). These conditions significantly heighten the risk of non-communicable diseases such as type-2 diabetes and cardiovascular disease, which are among the leading global causes of death (Mensah *et al.*, 2019). This is also true for Sweden, where more than half the adult population suffer from overweight or obesity (Public Health Agency of Sweden, 2023). Despite extensive research, overweight and obesity rates continue to climb, resulting in a global epidemic claiming over 2.8 million lives annually (The Lancet Gastroenterology, 2021; WHO, 2021b).

The fundamental reason for overweight and obesity is considered to be food overconsumption, which occurs when energy intake exceeds the energy expenditure of the body (WHO, 2021b). This is largely driven by increasingly common obesogenic food environments due to globalisation, urbanisation and rising income levels, also referred to as “nutrition transition” (Research Institute (Ifpri), 2017). However, food overconsumption often suffers from the simplification that weight gain is caused by people or populations consuming more energy than they expend (Swinburn *et al*., 2015). Despite ample evidence of complex underlying genetic and environmental causes, this simplification persists, leading to an assumption that people with overweight or obesity are personally responsible for their weight and contributing to obesity stigma (Westbury *et al*., 2023). Weight stigmatisation often leads to prejudice and discrimination in *e.g.* employment, healthcare and education settings, due to negative stereotyping of people with overweight and obesity as being lazy, less competent or unmotivated, which these individuals are left to cope with alone (Puhl & Heuer, 2009).

Addressing overweight and obesity involves challenges. The widespread societal stigma and misconceptions about personal responsibility impact the behaviour of *e.g.* healthcare personnel and also divert the attention of policy makers (Swinburn *et al*., 2015). Policy efforts focus on transitioning from animal-based to plant-based proteins to sustain food systems and mitigate environmental impacts. Overall, food overconsumption is largely considered a health issue, as reflected *e.g.* in the SDGs, where only SDGs 2 and 3.4 address overweight and obesity to reduce hunger and premature death from non-communicable diseases (UN, 2015a).

The negative health implications of food overconsumption are well known globally, but its environmental effects are less well studied. Some studies show that excessive food consumption significantly increases environmental impacts, including land use, soil loss, energy expenditure and pollution (Blair & Sobal, 2006). Excessive food intake also contributes to higher greenhouse gas emissions through increased fuel usage, food production and organic waste (Michaelowa & Dransfeld, 2008).

Moreover, excess food intake is rarely factored into food system models as food waste, but emerging studies consider it to be waste (Porter & Reay, 2016). These studies highlight how losses from excess food intake mirror consumer food waste, impacting food security and sustainability (Alexander *et al*., 2017; Franco *et al*., 2022). Others propose considering food eaten beyond bodily needs as metabolic food waste, resulting from excess body fat accumulation in the population (Serafini & Toti, 2016; Toti *et al*., 2019).

3.7 School meal schemes

School meal schemes provide an excellent opportunity to drive the sustainability of food systems. School meals can contribute to healthier diets for children, supporting their physical and cognitive development (Hayes *et al*., 2018). When offered to vulnerable children in low-income settings, school meals form a crucial social safety net combatting food insecurity and malnutrition and *e.g*. lowering barriers to girls attending school (Gelli, 2015; GCNF, 2022). In high-income countries, school meals are usually structured to support public health ambitions to boost healthy eating habits and combat rising levels of overweight and obesity (Aliyar *et al*., 2015).

Sweden, Finland and Estonia are among the few countries in the world providing universal school meals funded by tax money. This means that all children attending compulsory education receive a hot meal every school day, regardless of their parental income. In addition, guidelines are in place to ensure that school meals are nutritious, meeting one-third of the daily energy and nutrient needs of schoolchildren, but also that meals are eco-smart in terms of being both plant-forward and low food waste (Swedish Food Agency, 2022). However, a large proportion of the school meals provided go to waste, with estimates indicating that up to 20% of the total amount served becomes waste (Malefors *et al*., 2022a). Wastage of this magnitude may indicate substantial nutrient losses, unnecessary environmental impacts and missed opportunities to provide nutritious food to children. High acceptance of the food is the ultimate prerequisite, since school meals that do not end up eaten by schoolchildren serve no purpose, no matter how nutritious or eco-smart these meals may be.

3.8 Food waste prevention measures

During the past decade, there has been a rapid increase in published studies quantifying food waste at the consumption stage (Reynolds *et al*., 2019). As understanding of the magnitude of the food waste issue has increased and food waste reduction goals have been established around the globe, studies aiming to identify hotspots with the greatest potential for food waste reduction have emerged (Eriksson *et al*., 2019). In addition, there has been increasing interest in investigating food waste reduction measures that could successfully help achieve overall waste reduction goals.

In studies focusing on food waste prevention in school and university canteens, information campaigns have shown promising results. For example, Whitehair *et al*. (2013) found that simple prompt-type messaging significantly reduced food waste (-15%). Similarly, Malefors *et al*. (2022) saw a significant plate waste reduction (-35%) after an awareness campaign in school canteens. However, Ellison *et al.* (2019) observed only a modest reduction in plate waste in university canteens following an information campaign, and concluded that passive information may not be effective. This was echoed by Visschers *et al*. (2020), who found that providing information alone did not result in plate waste reduction, but that a reduction of 20% could be achieved through a combination of information campaign and offering smaller servings. Further, Martins *et al.* (2016) tested nutrition and food waste education and suggest involving both children and teachers for successful long-term outcomes in reducing plate waste and improving food habits. However, only a few of those studies used control groups to confirm their successful results or investigated the long-term effects of the interventions (Table 2). Thus, there is a need for more robust evidence on the effectiveness, *i.e.* food waste reduction potential, of food waste prevention measures (Reynolds *et al*., 2019).

Table 2. *Overview of studies investigating food waste prevention interventions conducted in various school canteens, including observed food waste reduction potential, and factors included/excluded from their assessments*

Author	Type of waste			Type of establishment	Intervention	Food waste reduction potential	Long term reduction	Control group	Sustainability assessment		
	Surplus	Serving	Plate						Environmental	Economic	Social
Ellison et al. 2017	-	-	+	University canteens	Information campaign	-4%	-	+	-	-	-
Eriksson et al. 2019	-	+	+	Pre-schools, schools, elderly care, hospitals	Quantification	-4-11%	-	-	-	-	-
Malefors et al. 2022	-	+	+	School canteens	Tasting spoons, awareness campaign, plate waste tracker, guest forecasting	Up to -49%	-	+	-	-	-
Martins et al. 2016	-	-	+	School canteens	Nutrition and food waste education	-6-34%	+	+	-	-	-
Schmidt et al. 2019	-	+	+	School canteens	Menu planning, portion sizes	-30%	-	-	-	+	-
Schwartz et al. 2015	-	-	+	School canteens	Menu planning	Quantified food intake that increased	+	-	-	-	-
Visschers et al. 2020	-	-	+	University canteen	Information campaign, portion sizes	-20%	-	-	-	-	-
Whitehair et al. 2013	-	-	+	University diner	Information campaign	-15%	-	-	-	-	-
Ayala et al. 2022	+	-	-	School canteens	Food recovery mobile app, food redistribution program	20 t/year	+	-	+	-	+

In addition to information campaigns, planning and changes to menus in terms of applying improved nutritional standards may be effective. One study obtained a food waste reduction of 30% through reducing production and portion sizes and adjusting the food components on the menu to better suit children's and adolescents' food preferences (Schmidt *et al*., 2019). In another study where a new food policy for school lunches was implemented, requiring one of three components to be a fruit or vegetable serving, a three-year follow-up concluded that the intervention increased fruit and vegetable consumption and also reduced plate waste (Schwartz *et al*., 2015).

Recent reviews on food waste prevention measures agree on the need for more standardised evaluation methods and metrics and consistent reporting of results (Goossens *et al*., 2019; Hecht & Neff, 2019; Reynolds *et al*., 2019). Goossens *et al.* (2019) evaluated various food waste prevention measures using a pre-defined assessment framework and saw great variation in how evaluations had been conducted, but with most evaluations being incomplete in terms of covering all three aspects of sustainability (environmental, economic and social) (Table 2).

3.9 Sustainability assessments of food waste prevention measures

Studies investigating surplus food redistribution have more commonly included sustainability assessments, often applying life cycle assessment (LCA) as a method, mostly with focus on the environmental impacts (Table 3). This is likely due to the common framing of surplus food as a waste issue (Johansson, 2021), leading to studies often comparing redistribution to other food waste management options. These studies have demonstrated the superiority of redistribution for human consumption over other food waste management options, such as animal feed, anaerobic digestion, composting, incineration or landfill, mainly from the environmental point of view (Eriksson & Spångberg, 2017; Albizzati *et al*., 2019; Damiani *et al.*, 2021; Cakar, 2022).

A few studies have included all perspectives of sustainability in their assessments. For example, Albizzati *et al*. (2021) quantified the impacts of various food waste management options using societal life cycle costing and concluded that prevention followed by redistribution were the best valorisation pathways for food waste. Bergström *et al*. (2020) compared different ways of redistribution and found that food bag donations generated the largest environmental benefits, while also pointing out the economic losses embedded in this type of activity. Using Input-Output methodology, Reynolds *et al*. (2015) investigated the environmental and economic efficiency of food rescue operations in comparison with composting and landfilling. They concluded that due to the large mitigation of environmental impacts compared with the other options considered, food rescue is a more low-cost method of obtaining food for the food-insecure than direct purchasing. At the same time, they noted that food rescue had a high waste generation rate and high economic activity cost, but is a more attractive waste disposal option due to its environmental and social impacts (Reynolds *et al*., 2015). A study by Cicatiello *et al*. (2016) used waste audits and composition analysis as a basis to measure the extent of food waste in retailing, assess its environmental, social and economic impacts, and evaluate the potential for reducing food waste through recovery efforts.

Table 3. *Overview of studies investigating surplus food redistribution, including method and factors included/excluded from their assessments*

Author	Country	Stage of FSC	Method	Quantification	Effectiveness	Efficiency	Rebound effect	Sustainability assessment		
								Environmental	Economic	Social
Albizzati et al. 2019	France	Retail to charity	Life cycle assessment	+	-	-	-	+	+	-
Albizzati et al. 2021	EU-27+1	Retail to charity	Societal life cycle costing	+	-	-	-	+	+	+
Bergström et al. 2020	Sweden	Retail to charity	Life cycle assessment, Life cycle costing, Social life cycle assessment	+	-	-	-	+	+	+
Cakar 2022	Turkey	Retail to charity	Life cycle assessment	+	+	-	-	+	+	-
Cicatiello et al. 2016	Italy	Retail to charity	Waste audit, composition analysis	+	-	+	-	+	+	+
Clare et al. 2023	New Zealand	Retail to charity	Social return on investment	+	-	+	-	-	+	+
Damiani et al. 2021	Italy	Produces and retail to charity	Life cycle assessment	(+)	-	-	-	+	-	-
Eriksson & Spångberg 2017	Sweden	Retail to charity	Life cycle assessment	+	-	-	-	+	-	-
Mirosa et al. 2016	New Zealand	Charities	Interviews	-	-	-	-	-	-	+
Mousa & Freeland-Graves 2019	United States	Charity to people in need	Food security and FFQ questionnaires, list of food donations	+	-	-	-	-	-	+
Reynolds et al. 2015	Australia	Retail to charity	Input-Output analysis	+	-	+	-	+	+	+
Vittuari et al. 2017	Italy	Charities	Literature review, interview, questionnaire	-	-	-	-	-	-	+
Wolfson & Greeno 2020	United States	People in need	Interviews	-	-	-	-	-	-	+

Social impacts have been the least investigated perspective of the three sustainability perspectives in studies using life cycle methodology, but have been more commonly investigated in studies using other methods. For example, Clare *et al*. (2023) used social return on investment methodology to measure the social value of different food rescue models in monetary terms, although most commonly applying qualitative methods including interviews. Vittuari *et al*. (2017) investigated the characteristics and various hotspots of redistribution activities through interviews, while Mirosa *et al*. (2016) explored the social value that food rescue enterprises can create for both their stakeholders and the wider community. A study by Wolfson & Greeno (2020) was one of the few to investigate recipients' perceptions and their use of rescued food, including its impact on their health and food insecurity. Similarly, Mousa & Freeland-Graves (2019) assessed social impact on the recipient, but from the nutrient intake perspective.

Overall, only a few studies have conducted a holistic assessment of surplus food redistribution, including all sustainability perspectives in addition to quantification or assessing its effectiveness, let alone including systemic effects, like the rebound effect (Thiesen *et al*., 2006) (Table 3). While surplus food redistribution can potentially accrue some savings for donation recipients, and lower environmental impacts, the net outcome depends on how the saved money is spent, which could either increase or decrease the intended environmental benefits. However, conducting more holistic studies that also include monitoring rebound effects could be challenging due to inflated costs (Reynolds *et al.*, 2019).

4. Materials and Methods

The work in this thesis comprised investigations of three theme areas, *food overconsumption*, *surplus food redistribution* and *plate waste prevention* (see Figure 1). The materials used in the work on each theme are described below, followed by an overview of the methods applied.

4.1 Materials

4.1.1 The case of food overconsumption

Examination of the amount of metabolic food waste (MFW) and its climate impact in Sweden (Paper I) commenced by considering a novel methodology applied by a study investigating MFW in Italy (Serafini *et al.*, 2016). However, replicating their method was not feasible, since they studied dietary intake patterns among a cohort of individuals with overweight and obesity to investigate the type and quantity of MFW, a data category unavailable in Sweden. This lack of data presented an opportunity to enhance the methodology in future studies.

Instead, a different approach was adopted, utilising national statistics on overweight and obesity prevalence in Sweden (SCB, 2019). While Serafini *et al.* (2016) based their calculations on excess body fat, in Paper I the analysis was extended to assess excess energy expenditure due to excess body weight. Assessing energy expenditure over time, rather than as a fixed amount of energy stored in body fat, gave a result in terms of units of measurement that was more intuitive to interpret and easy to compare with other food waste statistics, which are usually also expressed as a function of time. The caloric amounts were then converted into quantities of foods, *i.e.* MFW, based on the average intake patterns of Swedish adults investigated through a national dietary survey (Riksmaten-2012) (Amcoff *et al*., 2012). It was assumed that food overconsumption followed average food intake of males and females except for fruit, vegetables, coffee and tea, which were excluded as they were deemed not to contribute to overweight and obesity due to their low energy content. The calculations of excess energy intake and MFW are described in further detail in sections 2.1-2.3 in Paper I and the intake pattern in section 2.3 in Paper I (Table 1. *Swedish modified food intake*).

4.1.2 The case of surplus food donation

To investigate the sustainability outcomes of surplus food redistribution as a food waste management system, a Swedish non-profit organisation, Uppsala City Mission, was used as a case commencing in August 2020 (Papers II & III). Uppsala City Mission supports socially and financially vulnerable people in Uppsala City in various ways, *e.g.* by offering job training opportunities and rehabilitation. Another important support activity is surplus food redistribution from local retailers through two sub-units, a food bag centre and a soup kitchen. The food bag centre has operated since 2018 and in 2020 had 250 members receiving weekly food bags. The soup kitchen has operated within the current framework since 2016 and in 2020 had 12,175 visitors. The food bag members are charged a nominal fee of 250 SEK (~25 EUR) per six months, whereas the soup kitchen serves meals free of charge. In 2020, the food bag centre redistributed approximately 13,756 food bags, representing in total 170 metric tonnes (t) of surplus food, while the soup kitchen served approximately 34 t of surplus food as meals to people living in social vulnerability and homelessness.

An alternative food waste management scenario, a biogas plant located in Uppsala, Sweden, was used in Papers II & III to compare the environmental performance of surplus food donation to its likely alternative. In 2020, the biogas plant treated approximately 48,000 t of food waste originating from households and the retail and food service sectors (Uppsala Vatten, 2021). In addition to biogas, which is mainly used to fuel city buses, it also produces biofertiliser, which is used in crop cultivation.

4.1.3 The case of plate waste prevention

To investigate the sustainability outcomes of educational approaches to reduce plate waste in school catering, the public meal services of Uppsala

Municipality, Sweden, was used as a case (Papers IV-VI). They operate 180 kitchens, as a combination of production and satellite kitchens, serving approximately 45,000 meals per day to pre-school and schoolchildren, as well as elderly people. The meals are planned according to the guidelines of the Swedish National Food Agency, while also considering political decisions in the municipality and even service user preferences to the greatest degree possible. For the past decade, much attention has been paid to serving more plant-based meals and to sourcing food from local and/or organic producers, although availability and budget are constraints to fully meeting those goals. A meal planning system is used to ensure that school meals comprise 30% of schoolchildren's daily energy and nutrient needs.

4.2 Methods

To assess the sustainability outcomes of the measures assessed in this thesis, diverse data collection and analytical methods were used for each theme and paper, as illustrated in *Figure 3*. The main methods included LCA to assess the environmental impacts, social life cycle assessment (S-LCA) to assess the social impacts and cost-benefit calculation to assess the economic impacts. Various other methods, such as food waste quantification, composition analysis, material flow analysis, nutritional calculations, surveys and experimental studies were used to collect input data for the impact assessments and to derive various indicators, such as effectiveness, *i.e.* food waste reduction potential (*Figure 3*).

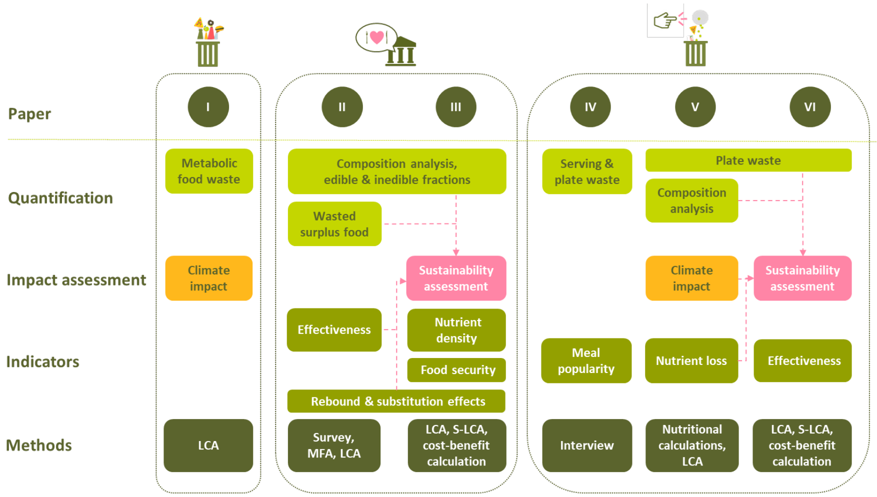

Figure 3. Overview of the data collection process and analytical methods applied to assess and evaluate the sustainability outcomes per paper and per theme in this thesis. Arrows indicate where knowledge gained in one paper contributed to the assessment in a following paper. Symbols represent:

 Food overconsumption  Surplus food donation  Plate waste prevention

4.2.1 Life cycle assessment

Life cycle assessment is a systematic methodology for assessing the environmental impacts associated with the life cycle of a product or a service. LCA has become a widely used methodology in studies evaluating environmental impacts of supply chains and end-of-life waste management, including food waste and its management options (Salemdeeb *et al*., 2017). The method is also used by the EU for food system analysis to support decision-making in selecting actions to minimise environmental impacts (EC, 2020b). One of the strengths of LCA is its ability to highlight hotspots and unveil trade-offs between different stages in supply chains and among environmental impact categories. In decision-making, however, LCA should not be used in isolation but in combination with other assessment methods, including economic and social assessments, to allow a more holistic view and to reveal trade-offs between the different aspects of sustainability (Goossens *et al*., 2019).

In this thesis, LCA was used to meet two different kinds of aims. First, it was used to assess the embedded environmental impact in food waste, including MFW and plate waste from school canteens in Sweden (Paper I). Using existing food-related LCA data to assess the climate impact enabled assessment of the embedded GHGE that were emitted in vain or could potentially be avoided through food waste prevention measures. Second, LCA was used to compare the environmental impacts of three food waste management options, food bag donations, soup kitchen donations and anaerobic digestion (Papers II & III), which were modelled in parallel with retail gate as a starting point (*Figure 4*). Applying LCA in this way allowed identification of the most environmentally friendly pathway for managing retail surplus food, where emissions generated by these waste management options were accounted for using site-specific input data when possible (for more details, see Appendix A in Paper III). Processes included in donation scenarios were transport to charity, energy for storage, packaging, transport home and food waste treatment. For anaerobic digestion, the processes included were pre-treatment (including transport), anaerobic digestion and outbound transport of the biofertiliser.

In addition to the immediate impacts of assessed processes, the life-cycle paradigm also requires consideration of the processes that occur in response to these (Field & Ehrenfeld, 1999). In the context of this thesis, substitution and rebound effects were considered the most important factors to include, due to the their potentially large contributions to the net impact results indicated by some previous studies (Eriksson & Spångberg, 2017; Albizzati *et al.*, 2022).

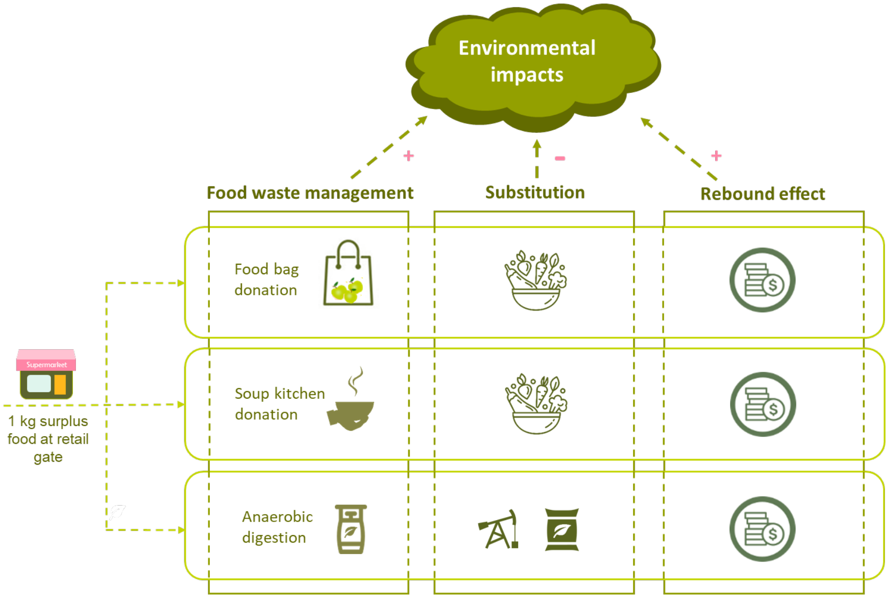

Figure 4. The three food waste management scenarios evaluated in terms of their environmental impacts in life cycle assessment: food bag donations, soup kitchen donations and anaerobic digestion. Substitution and rebound effects were included through system expansion and credited or added to calculate overall results.

Substitution

Substitution in the context of food donations was based on the assumption that prevention of food waste leads to a reduction in food production. However, this assumption is not based on evidence, as the extent to which food production is affected by food waste prevention is currently unknown (Caldeira *et al.*, 2019). Nevertheless, it is an expected long-term outcome, similar to the case of biofuel production, where the use of biofuels in industries and transportation has been shown to minimise dependence on fossil fuels (Ambaye *et al.*, 2021). Therefore, the environmental impacts associated with substituted products were credited to the environmental impacts, as illustrated in *Figure 4*.

In the context of food donations, substituted products comprised avoided food purchases due to receiving donated food. The substituted foods were investigated using a single 24-h dietary recall interview among the food donation recipients, based on the FAO dietary diversity questionnaire

(Kennedy *et al*., 2013), and composition analysis of 30 randomly selected food bags. For a complete list of food groups and items per food bag in grams, see Table C.1, Appendix C, in Paper III. Based on these investigations, the substituted foods were not deemed equal to the amounts and types of donated foods. Certain luxury food items, such as mango, chocolate and ready-made meals, were excluded and in total 90% of food bag weight was assumed to be substituted and 10% wasted. Further, the soup kitchen visitors were indicated to eat less when not visiting the soup kitchen, and therefore the soup kitchen donations substituted only two daily meals per visitor. For more details of the input datasets used for substitution, see Appendix B in Paper III.

In the anaerobic digestion scenario, the biogas produced substituted for natural gas in municipal buses and the biofertiliser replaced use of mineral fertiliser by local farmers. For more detailed input datasets for substitution, see Appendices B and C in Paper III.

Rebound effects

To date, rebound effects have mostly been studied in the context of energy efficiency improvements and how corresponding behavioural responses may result in increased energy use, and therefore lower overall emission savings than expected (Chitnis *et al*., 2013). In the context considered in this thesis, rebound effects were mainly expected to arise at the consumer level due to accrued monetary savings through receiving donated food by households (Thiesen *et al*., 2006). Second-order effects were not included, as these were deemed to be evened out by market mechanisms if they were to arise (Weidema, 2008). According to the self-administered questionnaire results among donation recipients, accrued savings amounted to 165 SEK per food bag and 25 SEK per daily soup kitchen visit, which were used to account for the rebound effects together with their associated consumption patterns.

Re-spending of the savings was considered to lead to additional environmental impacts, offsetting at least some of the expected emission savings achieved due to surplus food donations. According to previous research, the largest rebound effects were caused by measures undertaken by low-income households at the consumer level (Hagedorn & Wilts, 2019), making the consideration of rebound effects highly relevant in the present work. Rebound effects were also included in the anaerobic digestion scenario, although they were not expected to be significant due to being second-order effects, often resulting in negligible effects on consumption and production, and therefore diluted by the market mechanisms (Weidema, 2008).

The rebound effect was defined as the relationship between potential emission savings (ΔH) and emission savings that were not realised (ΔG) (Chitnis *et al.*, 2014; Druckman *et al.*, 2011):

$$Rebound\ effect = \frac{\Delta G}{\Delta H} \tag{1}$$

In LCA, the rebound-related emissions were modelled for each consumption category per product using the equation:

$$\frac{Accrued\ savings\ (SEK)}{Product\ price(\frac{SEK}{kg})} \times Product\ per\ category(\%) \times Spendings\ per\ category(\%) \tag{2}$$

For a complete list of the consumption categories, datasets and prices used in modelling related to donations and anaerobic digestion, see Appendix D in Paper III.

4.2.2 Investigating food waste reduction potential

Material flow analysis

Material flow analysis is a method for creating a graphical model of a well-defined system using two scientific principles, the systems approach and mass balance (Fischer-Kowalski, 1998). Using material flow analysis, the effectiveness of the surplus food donation system was examined in terms of eaten and wasted proportions of donated surplus food. The surplus food flows were quantified, starting from retail gate via charity units to recipients, including transport, allocations of surplus food between charity units and points where surplus food returned to waste stream. Surplus food input and its allocation between charity units were based on 2020 data obtained from the Uppsala City Mission, as described in section 2.1.1 in Paper II. Food waste streams were quantified at the food bag centre and based on estimates at the soup kitchen. Further, composition analysis of 30 randomly chosen food bags was conducted to quantify edible and inedible fractions of the food bag contents. Lastly, the quantity of post-consumer waste was derived from a self-administered questionnaire completed by the food bag subscribers.

The data collection is described in further detail in sections 2.1.2-2.1.4 in Paper II.

Meal popularity

To investigate the impact of meal popularity on the level of food waste generated in school catering, food waste quantification data and lunch menu data for 61 school canteens in Uppsala Municipality covering the period November 2019 to September 2021 were analysed (Paper IV). The median value was used to analyse ‘waste per guest’ (g), to reduce the impact of extreme values. The number of guests was counted based on the amount of plates used during the school lunches. To investigate which school meals were popular and which were unpopular, 17 kitchen staff from one preschool, seven primary and two upper secondary schools were interviewed through semi-structured interviews (Kvale, 1996) in March 2022.

The interview data were used to categorise the menus into ‘high acceptance’, ‘low acceptance’ and days with ‘both’ high acceptance and low acceptance meal options. Another categorisation was made based on the degree of vegetarian options served: a ‘mixed menu’, *i.e.* with both vegetarian and non-vegetarian meals being served and a ‘vegetarian menu’, *i.e.* with solely vegetarian meals being served. The quantitative analysis was then based on the categorisation results on popularity of meals and vegetarian meals. The quantitative data comprised 9262 observations. For more details on the study design and analysis, see sections 2.2-2.3 in Paper IV.

Educational approaches

To test the short and long-term effectiveness of educational approaches, including a plate waste tracker and pedagogic meals as plate waste reduction measures, an intervention study was conducted in 10 public elementary schools in Sweden during the period April 2020-May 2022 (*Figure 5*). Nine of the participating school canteens tested the plate waste tracker and five schools tested the pedagogic meals concept. Serving waste was measured in addition to plate waste, to rule out possible spillover effects if a significant plate waste reduction was observed. In addition, food waste data were collected from 55 other school canteens that had no known food waste-related interventions ongoing, to form a control group. For more details on data collection and analysis, see sections 2.2-2.5 in Paper VI.

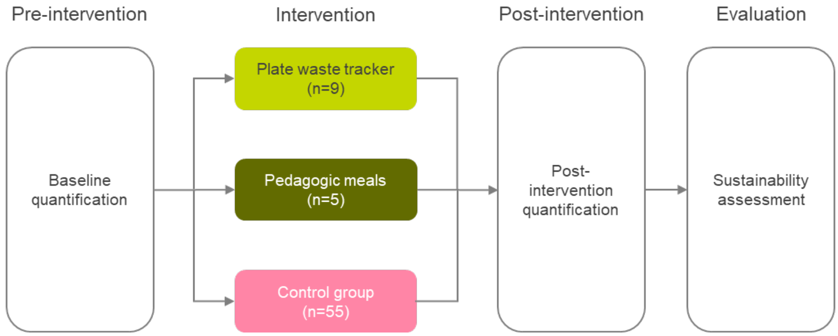

Figure 5. Design of the intervention study in which school meal plate waste prevention measures were tested and evaluated (Paper VI).

Plate waste tracker

The plate waste tracker intervention was designed to raise the awareness of canteen guests by using an interactive plate waste scale. When guests scraped their plates into a waste bin, a tablet connected to the scale underneath the waste bin displayed the amount of wasted food and its impact in terms of meeting the daily goal set for the total amount of plate waste.

Pedagogic meals

Pedagogic meals entailed food education in classrooms and in school canteens, designating school meals as a pedagogic activity. Previous research has suggested that pedagogic meals could facilitate long-term plate waste reduction (Martins *et al.*, 2016). Thus, teachers were asked to integrate themes such as food waste prevention and nutrition education into their existing curriculum. To facilitate implementation, voluntary teaching materials were provided in an on-line format. Teaching staff were instructed to follow a fixed framework of a minimum of 10 teaching occasions over 10 consecutive weeks. The food waste tracker was used to track the amount of plate waste generated in four schools throughout the intervention and in three schools at post-intervention measurement.

4.2.3 Economic impact assessment

The economic impact of the food waste reduction measures was assessed through analysing their *net economic benefits*. Assessing the net economic benefits is essential *e.g.* for ensuring that resources are used effectively, making informed decisions and enabling comparative analysis.

In the case of food donations, the net benefits were calculated as the difference between the societal economic benefits generated by the redistribution activities and the overall cost of the activities (Caldeira *et al.*, 2019). A key stakeholder perspective was applied to investigate the benefits and the costs, including recipients, retailers, volunteers, employees and donors, among others, as specified in Figure 3 in Paper III. For more details on specific calculation elements, see Table E.1, Appendix E, in Paper III.

In the case of plate waste prevention, the net economic benefits were calculated as the difference between the price of abated plate waste and the cost of implementing the food waste reduction measures. For more details on specific calculation elements, see 2.5.3 in Paper VI.

4.2.4 Social impact assessment

To assess the social impact of food waste reduction measures, the nutrient content of donated food and the nutrient loss embedded in plate waste were calculated to highlight the potential nutritional values preserved through the reduction measures. Additionally, the impact of food donations on the food security status of the recipients was investigated, using a survey as described below.

Food security questionnaire

As part of the self-administered questionnaire, the food security of the donation recipients was investigated using the six-item food security questionnaire developed by USDA (2012). Participants included 67 existing food bag recipients, 42 new food bag recipients and nine soup kitchen visitors, whose demographic characteristics can be seen in Table H.1, Appendix H, in Paper III. To evaluate whether food bags could contribute to the food security of the recipients, the mean scores for new and existing food bag recipients were compared.

Nutritional assessments

Nutritional calculations were conducted on the edible fraction of the composition data of food bags. The number of days on which the food bags met daily reference intake values (DRI) were investigated. The macronutrient contents were expressed as energy percent (E%) values in comparison to the Nordic Nutrition Recommendations (NNR) 2012 reference E% values. Micronutrients and dietary fibre were expressed as nutrient density (per MJ), which were then compared against the NNR (2012) reference values for recommended nutrient density (per MJ).

In addition, the composition of plate waste sampled from two elementary school canteens in Uppsala, Sweden, serving lunches to more than 300 daily guests aged 6-9 years, was investigated. Data were collected from both canteens for eight days in total. Data collection included all plate waste generated during the school lunches in the canteens, excluding beverages and kitchen and serving waste or food waste from breakfast. Complete separation was not always possible, due to some liquid waste (*e.g.* sauces) and mixed waste (rice with tiny pieces of vegetables), and such cases were categorised in terms of the main component (see Table A.2, Appendix, in Paper V for a complete list of waste component categories).

The energy, macronutrient, micronutrient and dietary fibre content of the plate waste were derived as mean values per kg plate waste and per guest. The macronutrient content was also expressed as E% and the micronutrient content as nutrient density (per MJ). The indicator wasted nutrient days (WND) was also calculated, referring to the number of days (in the context of this thesis, number of schoolchildren/day) on which the plate waste met 30% of the daily recommended intake (RI) values of the schoolchildren, which school meals are required to fulfil. Thus, the mean energy and nutrient values were divided by 30% RI values for children aged 7-10 years with an average physical activity level, according to reference values (Nordic Council of Ministers, 2023).

5. Results

Overall, the results showed considerable sustainability benefits from food waste prevention measures, where food could be eaten by humans instead of wasted. Food donation mitigated environmental impacts despite substantial rebound effects, and added social value to donation recipients in particular. Measures focused on plate waste in school canteens showed great potential to prevent food waste, which was found to be nutritious and could potentially help bridging gaps in the nutrient intake of schoolchildren if consumed instead of wasted. The results also revealed the magnitude of food overconsumption among the Swedish adult population, with considerable associated climate impact, highlighting a paradox that food consumption itself can become wastage of food with unnecessary environmental burden when food is eaten in excess of the energy needs of human bodies.

5.1 Food overconsumption

5.1.1 Quantity of metabolic food waste

Food overconsumption amounted to 699 billion kcal per year among Swedish adults in 2018. When converted to amount of food, *i.e.* MFW, the results showed an annual amount of 481 kt being wasted due to food overconsumption (Paper I). The food groups contributing most to MFW were: (i) dairy products; (ii) drinks (including alcohol but excluding coffee and tea); and (iii) sweets, snacks and fizzy drinks (soda) (*Figure 6*).

5.1.2 Climate impact of metabolic food waste

Metabolic food waste corresponded to 1210 kt of CO_2e per year. The food groups that contributed most to the climate impact were: (i) meat, fish and eggs; (ii) dairy; and (iii) other (*e.g.* pizza and pie), as shown in *Figure 6*.

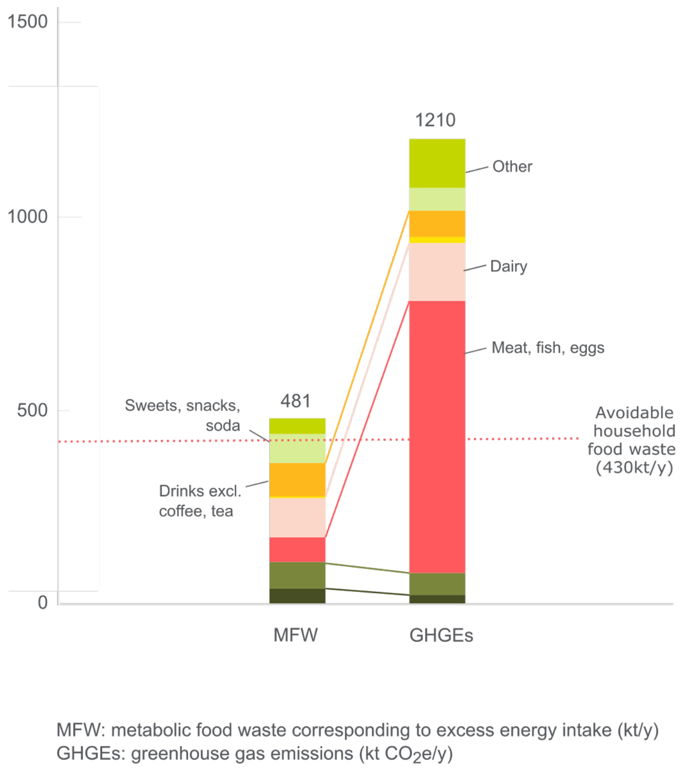

Figure 6. Amount of metabolic food waste (MFW, 481 kt/y) and amount of avoidable household food waste (430 kg/y) in Sweden. The climate impact of MFW amounted to 1210 kt of greenhouse gas emissions per year. The three food groups contributing most to MFW and climate impact (sweets, snacks and fizzy drinks/soda) are also indicated.

5.2 Sustainability outcomes of surplus food donation

5.2.1 Effectiveness of surplus food donation

The effectiveness of the surplus food donation system was 78%, as the total input of donated food was 237 t in 2020, of which 22% (53 t) was returned to the waste stream (*Figure 7*). The soup kitchen had a waste rate of 12%, while the food bag centre had a food waste rate of 25%. Of the total food waste, approximately 28 t (54%) was edible and 24 t (46%) was inedible (Paper II).

The food bag centre received 208 t of surplus food in total in 2020. After sorting according to the estimated remaining shelf-life, approximately 5% of the food was disposed of due to spoilage and 16 t was forwarded to the soup kitchen to be cooked into hot meals during the same day. In addition, the soup kitchen received 29 t of surplus food directly from retailers, thus redistributing 45 t of surplus food in 2020.

To optimise the system, food with the longest shelf-life was given away in food bags, or stored for later use, and food close to the expiry date was donated to other charities that could utilise the food within a short timeframe. One-third of the recipients also reported donating some of the food to people close to them, revealing that an additional informal food waste prevention measure was taking place. Similarly, the soup kitchen minimised its waste by allocating surplus food to various purposes such as daily catering at the premises, occasional food bags or other charities (Paper II). Thus the surplus food donation system functioned as a hybrid model of donation, combining functions as food bank and direct donations to salvage as much of the surplus food as possible (*Figure 7*).

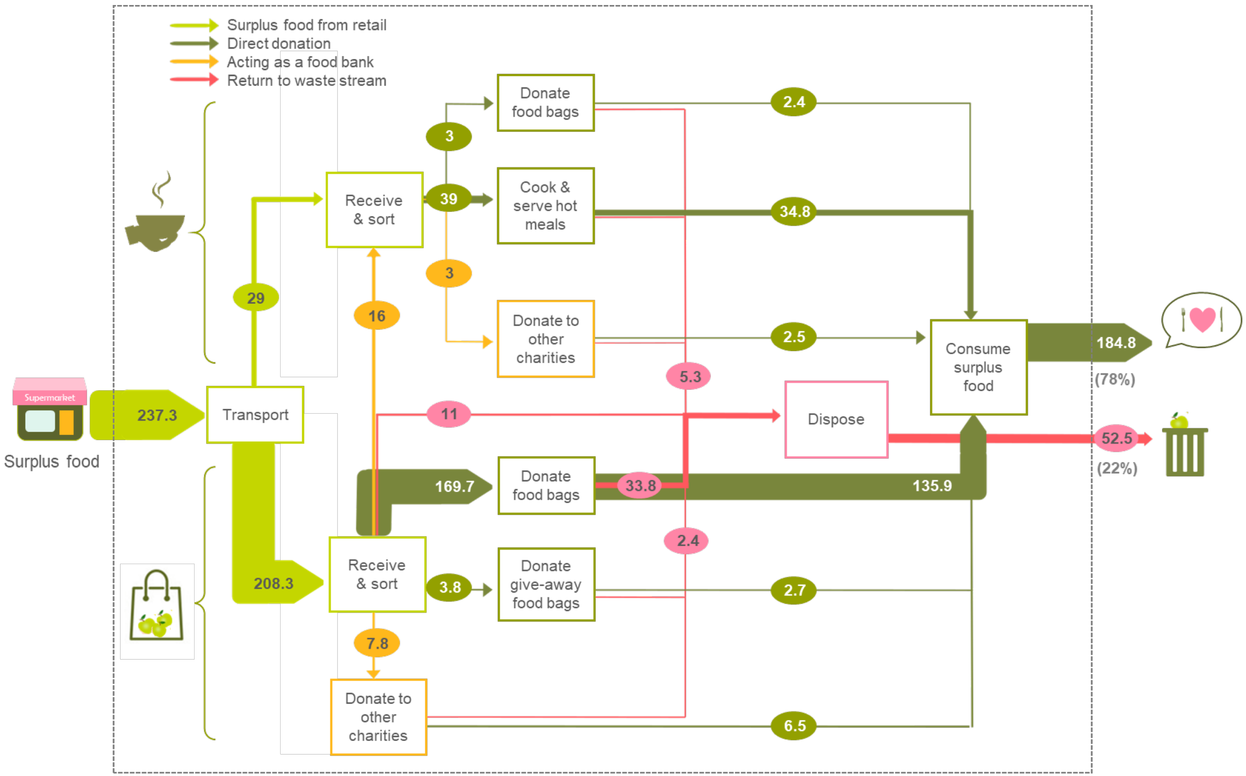

Figure 7. Material flow diagram of surplus food throughput via the food bag centre and soup kitchen of Uppsala City Mission in 2020. Redistribution was found to be effective, with 78% of the food eaten.

5.2.2 Environmental impacts of different scenarios

The results showed that the food bag donations outperformed soup kitchen donations and anaerobic digestion by generating the lowest environmental impact for 17 out of 18 midpoint indicators (see Table 2 in Paper III). The anaerobic digestion option generated the highest impacts in 11 out of 18 categories. In both cases, however, the impacts were mostly negative, indicating impact mitigation. The soup kitchen scenario performed slightly better than anaerobic digestion, with the highest environmental impacts in seven categories, while 11 indicators were negative, indicating impact mitigation. According to the endpoint level impacts, the food bag centre continued to outperform the other options in the ecosystem damage and human health impact categories, while anaerobic digestion performed worst (see Table 2 in Paper III).

Overall, the largest contributor to the net results was the substitution effect, while operational processes such as transport played only a minor role, as illustrated in *Figure 8* for the example of global warming potential (GWP). Some of the potential emission savings due to the substitution effect were offset by the rebound effect. For example, the rebound effect was 31% for food bags, 64% for the soup kitchen and 2% for anaerobic digestion with respect to GWP.

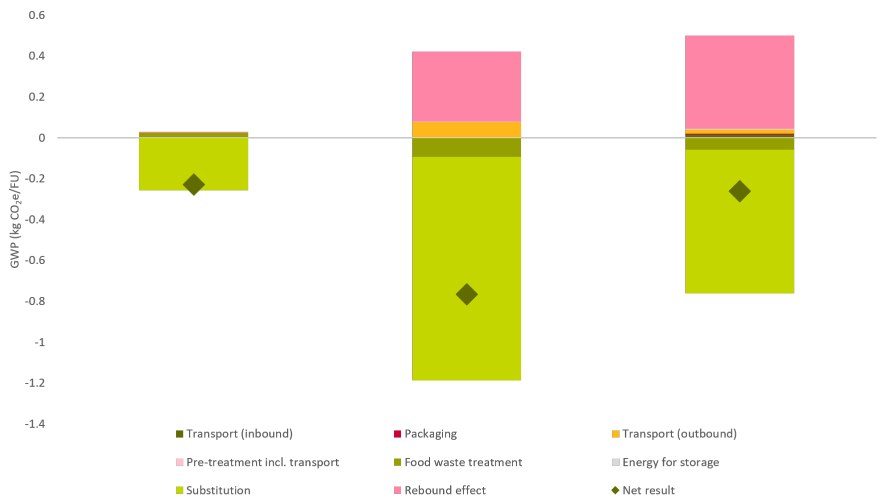

Figure 8. Net global warming potential (GWP) impact, broken down into emissions related to operations, substitution effect and rebound effect, for the three scenarios (anaerobic digestion, redistribution via food bag centre, and redistribution via soup kitchen).

Sensitivity analysis showed that both the rebound and substitution effects were sensitive with respect to changes in certain parameters. The rebound effects were highly sensitive to the amount of accrued savings (±SD = ±131 SEK for food bags; ±36 SEK for soup kitchen) and the proportion of savings spent on food (0%; 100%), leading to backfire effects in the soup kitchen scenario. The substitution effects were sensitive to changes in the amount of substituted food (50%; 70%). For more details on the sensitivity analysis, see section 4.1.1 in Paper III.

5.2.3 The net economic benefits of surplus food donation

Positive economic value was generated in the case of food bag donations, which had a net economic result of 1502 kSEK. In contrast, the soup kitchen had a negative net result of -622 kSEK, indicating that the benefits generated did not cover the costs of this redistribution activity. Overall, the net benefit calculations (see Table 3 in Paper III) revealed that various investments were required from different stakeholders to enable the redistribution activities. The greatest benefits were obtained by food bag recipients through accrued monetary savings (47%), followed by employees through salaries (35%), whereas the value transferred to retailers was negligible (only 1% of total benefits).

5.2.4 The social impacts of surplus food redistribution

The results suggested that food bags improved the food security status of recipients, with new recipients scoring 3.3 and existing recipients scoring 2.4 on a scale where 0-1 indicates high or marginal food security and 2-4 low food security. However, their food security status remained low even after receiving food bags.

The food bag contents indicated overall good quality of nutrients. The macronutrient content was balanced, with 12 E% of protein, 65 E% of carbohydrates and 24 E% of protein, and the fat content was of good quality. The bag contents were also low in sugar and salt, above reference value for dietary fibre and overall nutrient-dense (in line with reference values for most vitamins and minerals) (Table 5). Moreover, the average energy content of the food bags (43.439 kJ) met the average energy need of an adult person aged 31-60 years for approximately four days.

Table 4. *Average micronutrient and dietary fibre content of food bags in relation to reference values*

Vitamins, minerals and fiber		Mean	Reference value[a]	Number of days meeting reference value[b]	Nutrient density per MJ	Reference value[c]
Vitamin A (RE)	RE	5205	800	**6.5**	120	80
Vitamin D	µg	19	10	1.9	0.4*	1.4
Vitamin E	α-TE	69	9	**7.7**	1.6	0.9
Vitamin B1 (Thiamin)	mg	9	1.2	**7.5**	0.2	0.12
Vitamin B2 (Riboflavin)	mg	8	1.2	**6.3**	0.17	0.14
Niacin	NE	170	15	**11.3**	3.9	1.6
Vitamin C	mg	1394	100	**13.9**	32.1	8
Vitamin B6 Pyridoxine	mg	11	1.3	**8.8**	0.3	0.13
Vitamin B12	µg	9	2.4	3.9	0.2	0.2
Folate	µg	2467	400	**6.2**	56.8	45
Phosphorus	mg	6703	700	**9.6**	154.3	80
Iron	mg	53	14	3.8	1.2*	1.6
Calcium	mg	3954	1000	**4.0**	91.0*	100
Potassium	g	24	3.5	**6.9**	0.6	0.35
Magnesium	mg	2347	310	**7.6**	54.0	32
Sodium	mg	9110	2000	**4.6**	209.7	245
Selenium	µg	139	60	2.3	3.2*	5.7
Iodine	µg	478	150	3.2	11.0*	17
Zinc	mg	47	11	**4.2**	1.1*	1.2
Dietary fiber	g	190	25-35	**7.6**	4	3

[a]Codex Alimentarius nutrient reference values for vitamins and minerals (where nutrient reference values are based on the daily intake value that is estimated to meet the nutrient requirement of 98 percent of an apparently healthy individual, thus the RDI or RDA) for the general population, identified as individuals older than 36 months (FAO and WHO, 2019). Sodium not to be exceeded. Fiber according to NNR(2012).

[b]Number of days the nutrient content of one food bag meets the reference value of nutrient

[c]NNR (2012) reference values for recommended nutrient density (per MJ) used for diet planning purposes for groups of 6-65 years of age with a heterogeneous sex and age distribution. Sodium not to be exceeded.

*Value not meeting the reference value.

5.3 Sustainability outcomes of plate waste prevention

5.3.1 Food waste reduction potential

The results of plate waste prevention were promising, showing that less food waste was generated on days with popular lunch menus compared with days with unpopular meals, regardless of whether the menu included both vegetarian and non-vegetarian meals or was solely vegetarian (Paper IV). Additionally, educational approaches like the plate waste tracker demonstrated significant potential for reducing plate waste both in the short and long term (Paper VI).

Mixed menus

In the case of mixed menus, popular meals generated 11% less plate waste than unpopular meals. The sum of plate waste and serving waste was 49.5 g/guest for days with unpopular meals and 41.2 g/guest for days with popular meals on the menu, representing an overall reduction of 17% in food waste (*Figure 9*).

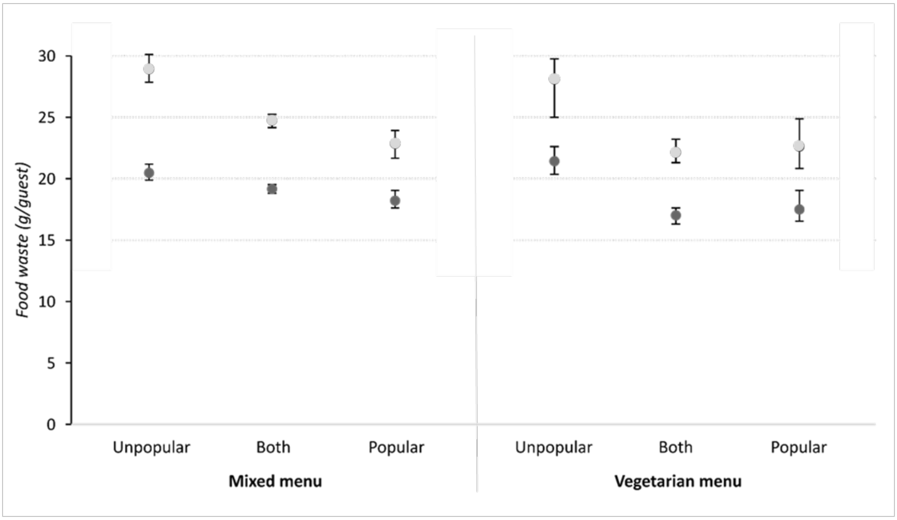

Figure 9. Food waste levels, divided into serving waste (●) and plate waste (●), of mixed and vegetarian menus, including unpopular and popular meals and a combination of the two.

Vegetarian menus

In the case of vegetarian menus, unpopular meals generated 19% more plate waste than popular meals. The sum of plate waste and serving waste was 49.6 g/guest on days with unpopular meals and 39.2 g/guest on days with popular meals on the menu, representing an overall reduction of 21% in food waste (*Figure 9*).

Educational approaches

Plate waste was significantly reduced, by 6 g (-26%) from the baseline of 23 g/guest to 17 g/guest, using the plate waste tracker (*Figure 10*). The reduction persisted in the long term, since at the post-intervention quantification the amount of plate waste was 18 g/guest, suggesting a significant reduction of 22% from the baseline. No changes were observed in the control group. A significant reduction of 19 g (-37%) from the baseline of 52 g/guest in serving waste was also observed and again persisted in the long term (-16 g or -31%). Accounting for the reduction that was simultaneously observed in the control group (-6 g or -21%), the total reduction in serving waste was 13 g or 25%.

The pedagogic meals intervention resulted in a plate waste reduction of 9%, from the baseline of 22 g/guest to 20 g/guest, although the reduction was not significant (*Figure 10*). However, at the post-intervention quantification, the plate waste level had significantly decreased by 14%, to 19 g/guest, for canteens that had used the plate waste tracker in measuring their plate waste. In contrast, for canteens measuring their plate waste manually, plate waste amount rebounded back to the baseline level of 22 g/guest. No changes were observed in the control group.

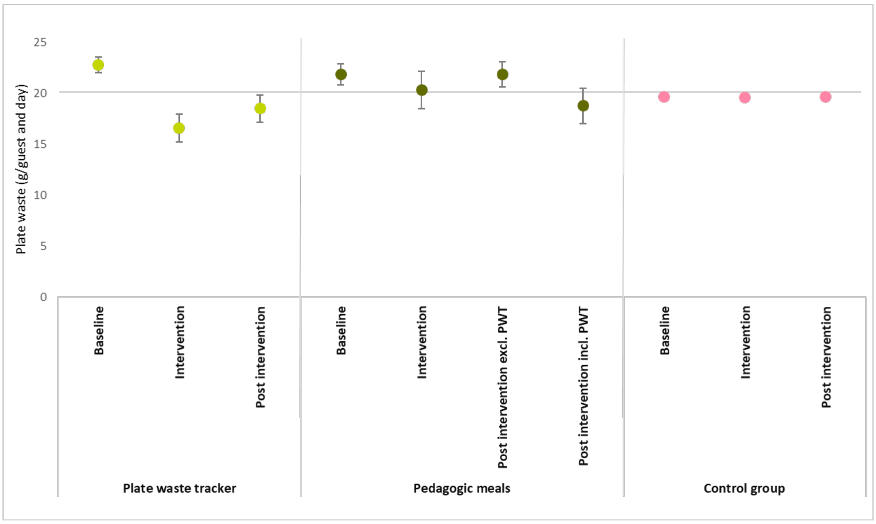

Figure 10. Serving and plate waste levels in the plate waste tracker and pedagogic meals interventions and in the control group. The values presented are waste levels in grams per guest and day for the baseline, intervention and post-intervention periods.

5.3.2 Environmental impact

Plate waste composition

The food categories comprising plate waste in the greatest amounts were staple foods, including: pasta 37 kg (28%), potatoes 25 kg (19%) and rice 16 kg (12%) (*Figure 11*). The least wasted foods included meat components, such as pork 2 kg (2%), beef 2 kg (2%) and chicken 3 kg (2%).

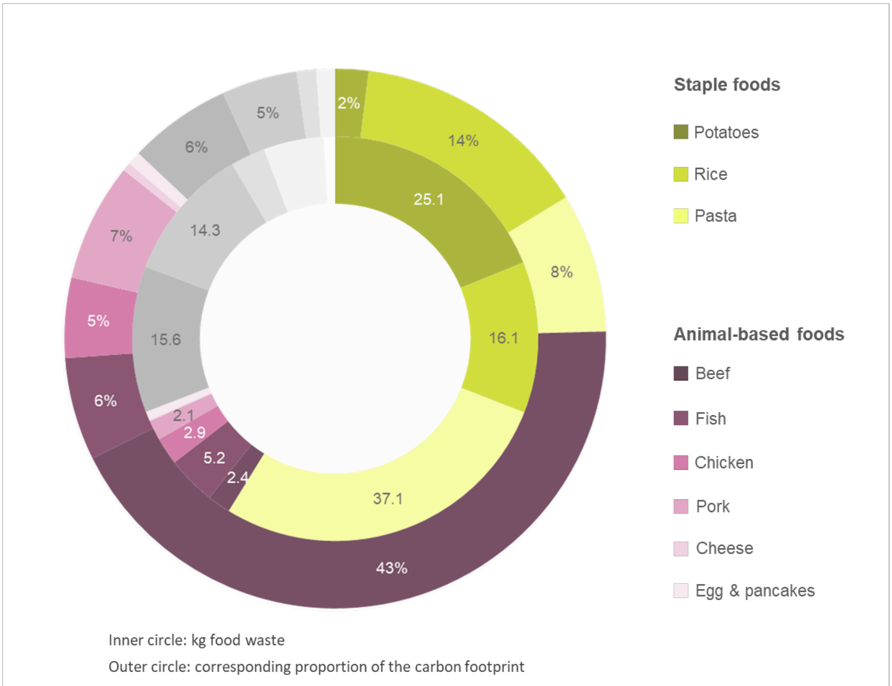

Figure 11. Total amount (kg) of food waste in different categories during the observation period (inner circle) and proportion of total carbon footprint (%) per wasted food category (outer circle). Animal-based food components were responsible for 10% of the total plate waste, but 63% of the total carbon footprint, whereas staple foods were wasted to the highest degree (59%), but responsible for only 24% of the total carbon footprint.

Carbon footprint embedded in plate waste

Total plate waste embedded approximately 127 kg of CO_2e over the eight-day observation period, corresponding to approximately 1.0 kg CO_2e per kg plate waste (Paper V). Staple foods such as pasta, potato and rice were responsible for only 24% of the total carbon footprint, despite representing the largest share of the total plate waste (59%) (*Figure 11*). On the other hand, animal-based foods (chicken, pork, beef, fish, cheese, and also eggs and pancakes) corresponded to only 10% of total plate waste, but were responsible for 63% of the total carbon footprint (*Figure 11*).

Environmental impact of plate waste reduction

The climate mitigation impact of the plate waste tracker intervention in terms of abated plate waste amounted to 279 kg CO_2e per school and year (Paper V). The climate mitigation impact for the abated serving waste amounted to 725 kg CO_2e per year and school.

5.3.3 Social impact

Nutrient loss embedded in plate waste

Energy and macronutrients

The edible part of plate waste contained approximately 4.8 MJ energy/kg. The protein, carbohydrate and fat content was 57 g, 171 g and 22 g per kg plate waste, respectively. The macronutrient content of the plate waste was balanced but protein-rich, with 20 E% of protein, 62 E% of carbohydrates and 18 E% of fat. In terms of WND, each kg of plate waste could have met the energy needs of two children and the protein needs of seven children.

Micronutrients

Overall, the findings showed significant loss of nutrients from uneaten food since the plate waste was micronutrient-dense, meeting or exceeding the recommended micronutrient density for planning a balanced diet except for four micronutrients (vitamin D, folate, iron, calcium) (Nordic Council of Ministers 2023). The plate waste also had a high amount of dietary fibre (3.9 g/MJ). Assessment of number of WND showed micronutrient losses of up to 11 days per kg plate waste. On average, the uneaten food from the canteens could have provided enough micronutrients to meet 30% of the daily needs of 4-94 schoolchildren per canteen, depending on micronutrient. For more detailed results, see section 3.4 in Paper V.

Social impact of waste reduction

The abated nutrient losses due to reduced plate waste when using the plate waste tracker amounted to approximately 1300 MJ of energy, 16 kg protein and 5 kg dietary fibre per school and year. The abated nutrient losses due to reduced serving waste amounted to 3500 MJ of energy, 41 kg protein and 14 kg dietary fibre per school and year.

5.3.4 Economic impact

The purchasing price of plate waste amounted to 33 SEK/kg (3 EUR/kg). The net economic benefits of the plate waste tracker amounted to 15,000 SEK (1300 EUR) per school and year. The net economic benefit of the pedagogic meals was -154,000 SEK (13,000 EUR) per school and year (Paper VI).

6. Discussion

The results obtained in Papers I-VI in this thesis revealed significant sustainability gains in preventing edible food from ending up in the waste stream through food consumption, either by donating surplus food or by preventing plate waste in school canteens. The results also revealed the climate cost of excessive food consumption among Swedish adults, emphasising the paradox of consuming food beyond the body's energy needs as a form of food waste.

6.1 Hidden climate impact of food overconsumption

The results revealed the magnitude of food overconsumption, *i.e.* MFW generated by adults in Sweden, where the estimated amount (481 kt/y) exceeded the amount of avoidable household food waste (430 kt/y). Further, the climate impact of MFW amounted to 1210 kt CO_2e/y, representing up to 10% of the food-related GHGE and 2% of the total GHGE in Sweden. Similar findings have been made in Italy, with MFW equating to annual household food waste of 1.6 million tonnes, corresponding to approximately 21% of GHGE from the Italian agriculture sector (Franco *et al.*, 2022). Thus the results highlight the significant hidden climate cost of a food waste component that is generally not acknowledged or targeted in waste reduction measures.

Although the results referred to the Swedish adult population, the global issue of overweight and obesity has surged over the past few decades. Despite over two decades of authoritative policy recommendations from organisations such as the WHO, no nation has managed to reverse the obesity epidemic, which in fact keeps accelerating (Roberto *et al.*, 2015; Phelps *et al.*, 2024). For example in India, one of the largest populations in the world, the adult prevalence of overweight is projected to more than double between 2010 and 2040, while the prevalence of obesity will triple (Luhar *et al*., 2020). In Sweden, the prevalence of adult overweight and obesity increased from 46% to 51% between 2006 and 2022 (Public Health Agency of Sweden, 2023). Similarly, childhood overweight and obesity in Sweden is expected to double from 10% in the early 2000s to around 20% by 2030 (Public Health Agency of Sweden, 2023).

The obesity issue is crucial, especially for children, as they often carry overweight and obesity into adulthood (Di Cesare *et al*., 2019). Treating or reversing adult overweight and obesity is challenging (Yang *et al*., 2022), and the prevalence increases with age (Lin & Li, 2021). Common strategies for managing obesity include exercise, dietary changes, bariatric surgery and in some cases the medication semaglutide, a drug for managing type 2 diabetes, which has been noted for its potential benefits in weight loss, with several ongoing clinical trials seeking effective treatments (Yang *et al*., 2022). However, prevention or early treatment is currently the best option to avoid health issues. While medical treatment is urgently needed by many for improved health, it is important to note that medicating overweight and obesity would treat symptoms and not the underlying causes, although it could help to halt the increasing trend.

The EU is proposing targets to halve per capita food waste by 2030 (De Laurentiis *et al*., 2023). In Sweden, household food waste, which makes up about 50% of the total of 1.1 Mt/year, is showing a decreasing trend but the level remains high (Hultén *et al*., 2024). Efforts to change consumer behaviour are being prioritised to address this issue (Swedish Food Agency *et al*., 2018). As MFW is not yet acknowledged as food waste, targets for its reduction are lacking, despite its amount exceeding that of avoidable household food waste. The Sustainable Development Agenda addresses overweight and obesity as part of its health targets, but its goals have been criticised for not being adequate to address the obesity pandemic and more systems-based approaches have been called for (Ralston *et al*., 2021). Given the previous failed attempts to address food overconsumption merely as a health issue, the world could be facing a scenario where the benefits of halving household food waste are overshadowed by an increasing amount of MFW.

However, recognising MFW as food waste component and framing overweight as environmentally wasteful in policymaking could risk leading to increased stigmatisation, which is one of the most pervasive challenges accompanying the disease (Swinburn *et al*., 2019; Westbury *et al*., 2023). As pointed out by Swinburn (2020):

> This social bias of being partly to blame for climate change would definitely not be applied to people who are more physically active (they also produce more CO_2 and require a higher food intake), but society's existing, largely unconscious, weight bias makes people with obesity an easy target.

Obesity must be addressed as a societal issue caused by systemic failures, instead of blaming the individual (Swinburn *et al*., 2015). While some advocate raising individual awareness to tackle MFW (Balan *et al*., 2022; Franco *et al*., 2022), others support a systems-based approach (World Obesity Federation, 2022). The failure to solve the epidemic has been attributed to *policy inertia* caused by three co-existing factors: (i) inadequate political leadership and governance to enact systemic policies needed; (ii) powerful commercial interests opposing policies needed; and (iii) public inactivity in demanding for the policies needed (Swinburn *et al*., 2019). Given the urgency of solving the climate crisis, framing overweight and obesity as a waste and/or climate issue could push policymakers to implement systemic changes such as sugar taxes or incentives for healthy food choices. Further, obesity could be linked up to 14 SDGs, instead of just two (Ralston *et al*., 2021). Sustainability could be included in food-based dietary guidelines and public meals could be extended to schools serving nutritious meals, as done in Sweden. Raising awareness about the fact that obesity is a chronic disease beyond an individual's willpower is also essential (World Obesity Federation, 2022).

6.2 Benefits and trade-offs of surplus food donation

The results presented in this thesis provide a more comprehensive view of the benefits generated by the food donation system, while revealing insights into associated trade-offs and their implications. Considerable sustainability gains were generated by the food donation system in terms of superior environmental mitigation in comparison with anaerobic digestion, while adding economic and social value to the recipients in particular. The system of donations was found to be effective, with 78% of the donated food eaten, but this also meant that the donation pathway was not free from food waste, as 22% of the surplus food redistributed from retail was returned to the waste stream. There were further drawbacks in terms of substantial rebound effects, offsetting some of the potential environmental benefits, but also in terms of dependence on economic investments from various stakeholders and surplus food free of charge to run the donations system.

Food donations significantly mitigated environmental impacts, outperforming anaerobic digestion, the prioritised waste treatment option in Sweden, in all but one impact category. For example, food bag donations reduced GWP by four-fold (-0.8 kg CO_2e) compared with anaerobic digestion (-0.2 kg CO_2e), despite a substantial rebound effect (31% for food bags, 64% for soup kitchens). These results are in line with the waste hierarchy and support findings in some previous studies (Albizzati *et al.*, 2019; Damiani *et al.*, 2021). This rebound effect, while a trade-off in environmental terms, provided economic and social benefits by relieving recipients' personal finances. This underscores the importance of considering multiple perspectives in sustainability assessments, aligning with arguments against producing biogas from edible food in large proportions (Johansson, 2021).

The good environmental performance of food donations was mainly due to the substitution effect, which was larger for food bag donations than soup kitchen donations (*Figure 8*). Further, the rebound effect offsetting some of the potential environmental gains was greater for the soup kitchen than food bags, making the net GWP result of food bag donations three-fold greater. Thus, in a strict environmental perspective, food bag donations were more effective. However, considering social aspects, soup kitchen donations were equally valuable, if not more, as recipients lacked sufficient food on non-visit days, also explaining the lower substitution effect and environmental benefit of soup kitchens.

Including the rebound effect in the environmental assessment may seem unfair, as it was caused by low-income people purchasing necessities they otherwise could not afford, while others in society are consuming much more. Low-income households have been associated with the largest rebound effects in previous studies, especially when implementing food waste reduction measures (Chitnis *et al.*, 2014; Hagedorn & Wilts, 2019). However, including the rebound effect ensured a more balanced, a systemic view of the sustainability impacts in the assessments in this thesis. Excluding it would perhaps make surplus food donations appear more environmentally friendly than they actually are in comparison with other waste management options. Overall, when planning policy measures to achieve certain ecological targets, it is critical to consider the rebound differentiations in income class in order to ensure that targets can be met (Hagedorn & Wilts, 2019).

An interesting finding was the benefit of a hybrid operation model, where the food bag centre and soup kitchen cooperated in handling both direct and indirect donations (thus also acting as food banks) (*Figure 7*). The food bag centre, receiving most redistributed food, swiftly sorted items daily, deciding their best use based on remaining shelf-life. The soup kitchen then cooked meals with items unsuitable for food bags, helping to achieve high effectiveness of the overall operation. The benefit of this hybrid model is supported by a study in the UK, which found that 40% of donated surplus food was returned to the waste stream from a single operating soup kitchen, suggesting that the hybrid approach may be more effective in redistributing surplus food (Alexander & Smaje, 2008; US EPA, 2023).

The results also indicated social benefits for recipients in providing balanced and nutrient-dense food due to the high proportion of perishable items, as also previously highlighted as a key benefit (Vittuari *et al*., 2017; Mousa & Freeland-Graves, 2019a, 2019b; Brennan & Browne, 2021). Although donations did not ensure food security, they had an alleviating effect, making recipients less food insecure. Importantly, recipients highly accepted the donated food, wasting only a little of it. This can be argued as the ultimate key success factor in enabling the positive sustainability values generated, as none of these would have been achieved had the donated food been returned to the waste stream. Thus, instead of focusing merely on measuring the amount of surplus food redistributed from retail, ensuring and monitoring the acceptance of donated food could be a valuable additional key performance indicator when evaluating surplus food donation operations (Caldeira *et al*., 2019).

Surplus food donation is widely advocated within the EU and often promoted as a win-win solution to food waste and food insecurity. However, this policy has also faced criticism, including concerns about recipient stigmatisation, greenwashing and shifting responsibility from the state to civil society (Millar *et al*., 2020; Roe *et al*., 2020). Critical questions arise, such as whether we want a system to help people in need that depends on the availability of food waste, or a system to reduce food waste that depends on the presence of people in need. These questions highlight potential ethical and practical issues within the current food donation framework.

Despite the positive outcomes in this thesis, it is important to emphasise that food donation should be considered a short-term solution while actively pursuing long-term strategies to address both food insecurity and food waste. Food donations cannot resolve food insecurity, as they do not address the root cause, *i.e*. poverty (UN, 2024c). Similarly, food donations do not tackle the underlying cause of food waste, which is overproduction. However, there is a risk of falsely perceiving the issues as solved, thereby delaying more effective, long-term solutions (Caraher & Furey, 2017). Establishment of infrastructure, regulations, norms, governing roles, practices, processes, jobs and benefits around food donation systems could potentially create a lock-in effect, making what was intended as a short-term solution more permanent (Messner *et al*., 2020). Moreover, surplus food waste becoming a resource for which there is a demand may paradoxically maintain the creation of food surpluses (Närvänen *et al*., 2020; Rao *et al*., 2023).

While minimising surplus at source is a key sustainable solution to food waste (Papargyropoulou *et al*., 2014), some surplus food may be inevitable. On the other hand, surplus food redistribution often remains small-scale, due to logistical challenges and high dependency on volunteers and financial support, representing a fraction of the total surplus food volumes generated (Midgley, 2014; Gram-Hanssen *et al*., 2016; Johansson, 2021). Thus, as such, surplus donation does not have to stand in the way of surplus food prevention at source. However, to provide clarity for all stakeholders in the food donation landscape, policy measures advocating food donations should be viewed from a broader perspective. This could include *e.g*. evaluating and setting goals for all the alternatives promoted by the food waste hierarchy and monitoring their progress, to ensure a balanced and effective approach aligned with broader sustainability objectives (Rao *et al*., 2023).

6.3 Sustainability of plate waste prevention measures

Investigation of plate waste prevention in school canteens revealed significant potential for reducing food waste through menu planning and educational approaches. By shifting to popular meals, whether vegetarian or not, food waste could be reduced by up to 21%. Use of a plate waste tracker, which aimed to raise awareness among canteen guests, showed reduction potential in plate waste of 26%, a reduction that was maintained in the long term. In addition, serving waste decreased by 25%, a reduction also maintained in the long term. Moreover, composition analysis indicated that the embedded climate impact of plate waste was 1.0 CO_2e/kg, and the economic loss was 33 SEK/kg. Significant nutrient losses were also embedded in plate waste, including 4.8 MJ of energy, 57 g of protein and 19 g of dietary fibre per kg waste. Overall, the results indicated substantial sustainability gains when school meals end up in the stomach of schoolchildren rather than in the bin.

The food waste reduction potential reported in this thesis is one of the few research findings of both short- and long-term reduction potential, as confirmed by the use of a control group in the context of school meals. One previous study investigated the long-term effect of revised nutrition standards on food intake and food waste in primary schools in the United States (Schwartz *et al*., 2015). Their three-year follow-up showed a significant increase in food consumption and a significant lowering in plate waste. Another study investigated the effect of education and information campaigns among schoolchildren and teachers in Portuguese primary schools at one week and at three months post-intervention, as confirmed against a control group (Martins *et al*., 2016). However, the findings in that study showed no long-term reduction in plate waste.

Overall, there is a need for more studies confirming the long-term reduction potential of food waste measures. This thesis showed that the plate waste tracker approach has good long-term reduction potential, even with a baseline of a lower span of 23 g/guest. The plate waste tracker also reduced serving waste, showing that its awareness-raising effect was not limited to the guests but also extended to kitchen staff, as found in a previous study (Malefors *et al.*, 2022b). The plate waste tracker has another potential advantage over other educational approaches by directly targeting waste makers rather than addressing all schoolchildren, including those who do not waste any food. A previous study found that the most plate waste (60%) was generated by a small minority of canteen guests (20%), while 40% of guests did not waste any food (Malefors *et al*., 2024), leaving an open question of how to identify the waste makers and reach out to them. The plate waste tracker could perhaps be used to test various messages aimed at waste makers, without having to single them out personally.

Composition analysis revealed that plate waste was nutritious, rich in dietary fibre (19 g/kg plate waste) and various vitamins and minerals. Each kg of plate waste could provide three schoolchildren with 30% of their daily dietary fibre needs (which school meals must fulfil), which is significant given the fibre intake gap among Swedish schoolchildren (Swedish Food Agency, 2003; Osowski *et al*., 2015). Surprisingly, the plate waste was also protein-rich, containing 20 E% of protein, despite comprising only a fraction of animal-based components (10%) and mostly plant-based staple foods (59%). Despite parental concerns about protein adequacy with increasing amount of plant-based school meals (Uppsala Nya Tidning, 2022), each kg of plate waste could provide seven children with 30% of their daily protein needs, suggesting that these concerns are likely unfounded.

The results also showed that the tracker generated a positive net economic benefit of 15,000 SEK per school annually, paying for itself in the first year. The whole sum would not be money in the pocket, since roughly one-third of the abated food waste would be eaten, and thus still produced, but the money would no longer be spent in vain. Conversely, the net benefit due to reduced serving waste, roughly two-thirds of the sum, could potentially be saved in production costs.

If the plate waste tracker were to become best practice in all Swedish primary schools, producing 200 million meals annually at an average cost of 30 SEK and carbon footprint of 0.8 kg CO_2e per meal, this would mean a net benefit of roughly 48 MSEK (4 MEUR) saved in production costs in the first year, corresponding to around 1% of the total meal costs. Similarly calculated, the climate mitigation of the plate waste tracker would amount to an annual mitigation of 3.5 million kg CO_2e, corresponding to approximately 2% of the total carbon footprint of Swedish school meals. In this case, the emissions from the plate waste tracker's production and implementation were considered negligible as shown by Obersteiner et al. (2021), and were therefore excluded from the calculation.

In addition to reducing food waste, Swedish public meals are responding to the pressure to become more climate-smart by increasingly serving plant-based instead of animal-based meals, aiming for a carbon footprint goal of 0.5 kg CO_2e per portion by 2030 (Swedish Food Agency, 2022; Uppsala Municipality, 2023). Some studies have shown promising results in serving GHGE-reduced (up to -26%), nutritionally adequate school meals without compromising meal acceptance (Eustachio Colombo *et al*., 2020; André *et* *al*., 2024). Indeed, for school meals to nourish children effectively, they must be eaten, requiring high acceptance among students. Strategies to increase intake while reducing waste only work effectively if the right foundations are in place, *i.e*. food is acceptable, culturally appropriate and nutritious (WWF-UK, 2023). The results in this thesis suggest that reducing unpopular meals in exchange for offering popular and nutritious meals is crucial. Moreover, serving popular vegetarian meals was shown not to be a waste generator, benefiting both planetary and children's health. Given the increasing prevalence of childhood overweight and obesity, school meal schemes are becoming increasingly important in attempts to create healthy food environments equally for all schoolchildren to curb the increasing trend (GCNF, 2022; Public Health Agency of Sweden, 2023). Even in this context, high food acceptance plays a key role, as long as the meals served are balanced and nutritious. Moreover, it is of the essence that plate waste reduction measures are designed so that school meals end up in the stomach of schoolchildren, instead of the bin or becoming serving waste, to promote healthy food intake and thereby displace unhealthy food choices.

7. Conclusions

There is an imbalance in global food consumption, with some overconsuming and others not getting sufficient food, while at the same time unacceptably high amounts of edible food are wasted. This thesis investigated ways of preventing food waste through food consumption and the sustainability impacts of such measures. In addition, the paradox of wasting through consuming food in excess was investigated. An overall conclusion was that reversing the imbalance, *i.e.* limiting food overconsumption and re-directing surplus food that would otherwise be wasted to human consumption, would bring considerable sustainability benefits, both for the planet and human health. More specifically:

- The magnitude of food overconsumption, measured as MFW in Sweden, was found to be substantial, 480 kt/year, indicating a considerable hidden climate cost 1200 kt CO_2e/year. To reverse an increasing trend, a reduction in MFW should be prioritised on the policy agenda, addressing it as a systemic failure, not just for human health but also for planetary health.

- Surplus food donation in the case studied was effectively organised in a hybrid model of operating and swift handling to divert edible food waste from the waste stream to people in need, resulting in 78% of the donated food being eaten.

- Surplus food donation mitigated environmental impacts to a greater degree than anaerobic digestion (*e.g.* three-fold in terms of GWP), despite substantial rebound effects (31-64%), while generating social value to recipients due to high acceptance of the donated food.

- As well as mitigating environmental impacts, surplus food donation also relieved personal economies and to some degree food insecurity of the recipients, while generating positive economic value (1502 kSEK in net benefits for food bag scenario). Despite these benefits, food donation should only be regarded as a short-term solution due to its inability to solve the underlying causes of food insecurity and food waste, including poverty, inequality and overproduction.

- Surplus food from retail and plate waste from school meals were both nutritious, offering significant nutrient savings when salvaged for human consumption, conveying social gain. Surplus food donations had the potential to improve recipients' nutrition, as the nutrient content of food bags was well balanced, with 12 E% protein, 60 E% carbohydrates, and 24 E% fat. The donations also scored high in nutrient density (e.g., 4 g/MJ dietary fibre) due to a large proportion of perishable food items, which were highly accepted by recipients. Plate waste prevention could play an important role in bridging gaps in the nutrient intake of schoolchildren, particularly dietary fibre, as plate waste is rich in fibre, containing 3.9 g/MJ.

- Serving popular vegetarian school meals and using plate waste trackers in school canteens showed significant long-term potential for food waste prevention (up to 21% and 24%, respectively), mitigating environmental impacts. These types of measures could be considered best practice due to their effectiveness and cost-effectiveness as food waste prevention measures but also due to their ability to positively influence the food intake of schoolchildren, which could be crucial in terms of preventing MFW.

8. Future research

Sweden is on the way to missing the goal of halving its food waste by 2030 (Hultén *et al*., 2024). Although some reduction has been achieved, the rate of reduction is currently too slow throughout the whole food supply chain, which is also true in the global context (UNEP 2024). The following suggestions for future research could help to accelerate the pace of food waste reduction both in Sweden and globally:

- *Taking policy action toward MFW*. The hidden amount and climate impact of MFW in Sweden are substantial, a trend likely applicable in many countries due to the high global prevalence of overweight and obesity. As this prevalence is projected to increase for decades, global-scale studies are essential. These studies should aim to highlight the magnitude of hidden food waste and its climate costs for policymakers. Additionally, they should include projections of the rising rates of overweight and obesity and model various policy actions to identify the most effective strategies for reversing these trends. This dual approach benefits both human and planetary health.

- *Addressing systemic food waste in the retail-consumer nexus*. While surplus food donations provide benefits such as mitigating environmental impacts and alleviating personal economic burdens, they do not tackle the root causes of food waste and food insecurity. Future research should focus on identifying and understanding the causes that lead to retail surplus food, often embedded in systems. By uncovering these underlying causes and the barriers that prevent change toward preventing waste, we can address this systemic food waste through implementing structural changes to transition to a more sustainable food system.

- *Implementing food waste prevention measures in school canteens*. The plate waste tracker showed great potential as a best practice for combating food waste in school canteens. Future studies should aim to confirm its impact on food production and consumption, highlighting its benefits in terms of cost savings and increased intake of schoolchildren. To maximise its effectiveness, research should also explore how to best use the food waste tracker in communication with waste generators. Additionally, overcoming barriers to implementing these successful measures on a larger scale, not only in school canteens but also in other types of organizations within the hospitality sector, should be a focus of future research.

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Popular science summary

Imagine throwing away every third meal you cook. Sadly, this is not hypothetical, as one-third of all food produced globally is wasted. Meanwhile, overeating is a growing problem and can also be seen as wasting food (metabolic food waste), while billions go hungry. This waste harms the environment, costs a lot of money and raises ethical issues, as food is a basic human right.

In the past decade, food waste has received much attention in research. The number of articles on this topic has skyrocketed, and a quick Google search for "food waste" reveals many pages from esteemed institutions like Harvard and the UN explaining the negative impacts of food waste. Civil organisations and influencers are campaigning against food waste, while agencies like the Swedish Food Agency offer tips on reducing it. There is widespread agreement on the need to reduce food waste.

Despite this consensus, reducing food waste is challenging. While research has revealed the scale and impacts of food waste, this is just the beginning. Current guidelines prioritise food waste prevention and managing food waste through *e.g.* donations, but too much edible food still gets wasted. Globally, most food waste ends up in landfills or dumps, while in Sweden it is mainly burned for energy or turned into biogas, with only a small amount reused for its intended purpose—to feed people.

To help policymakers, it is crucial to understand both the food waste issue and the benefits of potential solutions. Therefore, this thesis examined the environmental impacts of overeating and the benefits of food waste prevention through food consumption. This included donating surplus food from supermarkets and preventing plate waste in school canteens.

The results showed that overeating by Swedish adults had a large environmental impact, making up 10% of the national food-related climate impact. Preventing food waste by consuming it had both environmental and social benefits, such as reducing climate impact and nutrient losses. However, these benefits depended on high acceptance of the food. Wasted food was found to be highly nutritious and valuable. Preventing plate waste in school canteens could potentially help children obtain nutrients they often lack in their diet, such as dietary fibre, and help to reduce metabolic food waste. Donated food helped people in need, relieving their food insecurity and saving money, which they could spend on other essentials. However, ethical questions arise, such as whether we want to have a system to reduce food waste that depends on having people in need, or whether we want to have a system to help people in need that depends on having food waste. Therefore, surplus food donation is recommended as a short-term solution only, while we need to dig deeper to solve the underlying causes of food waste and food insecurity.

Ultimately, the results in this thesis suggested that reducing overeating is necessary not just for health, but also for environmental reasons, and that redirecting edible food waste to people not only helps the environment, but also provides valuable nutrients, offering potential health benefits.

Populärvetenskaplig sammanfattning

Tänk dig att du slänger var tredje måltid du lagar och vad det skulle göra för din ekonomi, klimat och miljö. Tyvärr ser det ut så här idag då en tredjedel av all mat som produceras globalt går till spillo. Samtidigt är överätning ett växande problem och kan också ses som slöseri med mat (metaboliskt matsvinn), samtidigt som miljarder människor går hungriga. Detta slöseri skadar miljön, kostar mycket pengar och väcker etiska frågor, eftersom mat är en grundläggande mänsklig rättighet.

Under det senaste decenniet har matsvinnet fått stor uppmärksamhet inom forskningen. Antalet artiklar i ämnet har skjutit i höjden, och en snabb Google-sökning på ”food waste” (matsvinn) visar många rapporter från ansedda institutioner som Harvard och FN och som förklarar de negativa effekterna av matsvinn. Civila organisationer och influensers driver kampanjer mot matsvinn, medan myndigheter som Livsmedelsverket ger tips om hur man kan minska matsvinnet. Det finns en utbredd enighet om behovet av att vi behöver minska matsvinnet.

Trots denna enighet är det en utmaning att minska matsvinnet. Forskning har visat på omfattningen av och effekterna av matsvinn, men det är bara början. Nuvarande riktlinjer prioriterar förebyggande av matavfall och hantering av matavfall genom t.ex. donationer, men alltför mycket ätbar mat går fortfarande till spillo. Globalt sett hamnar det mesta av matavfallet på deponier eller soptippar, medan det i Sverige huvudsakligen bränns för energiändamål eller omvandlas till biogas, och endast en liten del återanvänds för sitt avsedda ändamål - att föda människor.

För att hjälpa beslutsfattare är det viktigt att förstå både problemet med matavfall och fördelarna med potentiella lösningar. I den här avhandlingen undersöktes därför miljöpåverkan av överätning och fördelarna med att förebygga matsvinn genom matkonsumtion. Detta inkluderade donation av överskottsmat från stormarknader och förebyggande av tallrikssvinn i skolmatsalar.

Resultaten visade att överätning hos vuxna svenskar har en stor miljöpåverkan och stod för 10% av den nationella livsmedelsrelaterade klimatpåverkan. Att förebygga matsvinn genom att konsumera maten har både miljömässiga och sociala fördelar, såsom minskad klimatpåverkan och minskade näringsförluster. Dessa fördelar är dock beroende av att maten accepteras i hög grad. Det visade sig att den mat som slängdes var mycket näringsrik och värdefull. Att förebygga tallrikssvinn i skolmatsalar kan potentiellt hjälpa barn att få i sig näringsämnen som de ofta saknar i sin kost, till exempel kostfiber, och bidra till att minska det metabola matsvinnet. Den donerade maten hjälpte behövande människor genom att minska deras osäkra livsmedelsförsörjning och spara pengar som de kunde lägga på andra viktiga saker. Det uppstår dock etiska frågor, till exempel om vi vill ha ett system för att minska matsvinnet som är beroende av att det finns människor i nöd, eller om vi vill ha ett system för att hjälpa människor i nöd som är beroende av att det finns matsvinn. Därför rekommenderas donation av överskottsmat endast som en kortsiktig lösning, medan vi måste gräva djupare för att lösa de underliggande orsakerna till matsvinn och osäker livsmedelsförsörjning.

I slutändan tyder resultaten i denna avhandling på att det är nödvändigt att minska överätning inte bara av hälsoskäl utan också av miljöskäl, och att omdirigering av ätbart matavfall till människor inte bara hjälper miljön utan också ger värdefulla näringsämnen, vilket ger potentiella hälsofördelar.

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Full length article

The climate impact of excess food intake - An avoidable environmental burden

Niina Sundin[a,*], Magdalena Rosell[b], Mattias Eriksson[a], Carl Jensen[c], Marta Bianchi[d]

[a] Department of Energy and Technology, Swedish University of Agricultural Sciences, Box 7032, Uppsala 75007, Sweden
[b] Department of Biosciences and Nutrition, Karolinska Institutet, Stockholm, Sweden
[c] Department of Built Environment RISE - Research Institutes of Sweden, Gothenburg, Sweden
[d] Department of Food and Agriculture, RISE - Research Institutes of Sweden, Gothenburg, Sweden

A R T I C L E I N F O

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A B S T R A C T

The environmental impacts of food systems and the health consequences of excess food intake are well-acknowledged global issues. However, the climate impact of excess food intake, or metabolic food waste, has received less attention. This study estimated the amount of metabolic food waste and its climate impact in Sweden. Excess food intake was estimated based on the adult overweight and obesity prevalence in Sweden, by applying two alternative calculation methods, one based on the energy content of excess body fat, and the other based on the excess energy intake due to excess body fat. These caloric values were translated to food consumption patterns according to three dietary scenarios and their climate impact estimated based on carbon footprint data. The results showed that the annual amount of metabolic food waste represented 480–710 kt of food in Sweden and, regardless of dietary scenario, exceeded the annual amount of avoidable household food waste. The estimated greenhouse gas emissions from the metabolic food waste amounted up to 1.2 Mt CO_2e annually, accounting for approximately 2% of the total and 10% of the food-related climate impact in Sweden. This study confirms the magnitude of the hidden climate cost of excess food intake on a national level and emphasizes the importance of taking this aspect into consideration in actions to improve both planetary and human health. Although applied to the Swedish context, the methodology used in the present study could also be used to assess the environmental impact of excess food intake in other countries globally.

1. Introduction

Modern food systems are largely unsustainable, posing a threat to global food security, partly because of the high environmental impact of food production and consumption. The agricultural sector is in fact a major user of finite natural resources such as freshwater and land, contributing e.g., to soil degradation, deforestation, and loss of biodiversity (FAO, 2018). Moreover, industrialized food systems account for 19–29% of the total global anthropogenic greenhouse gas emissions (GHGEs), making them a major contributor to climate change, the defining challenge of our time (Vermeulen et al., 2012).

Another aspect of the unsustainability of food systems is food loss and food waste generated throughout the supply chain from agricultural production to household consumption. Approximately one-third of the food produced globally for human consumption is either lost or goes to waste, accounting for up to 5.9 Gt carbon dioxide equivalents (CO_2e) in annual GHGEs (Gustavsson et al., 2011; Porter and Reay, 2016). The costs of global food wastage are considerable. While the global food and grocery retail market was valued at US$11.7 trillion in 2019, the costs related to global food wastage were estimated to reach US$2.6 trillion annually with economic, environmental, and social costs included (FAO, 2014; GVR, 2020a). Further, the food waste management market was valued at US$30 billion with a projected annual growth rate of 5.4% until 2027 (GVR, 2020b). While food waste treatment facilities are a necessity, investments in such infrastructure could also entail lock-in effects leading to an unwillingness to reduce food waste (European

Abbreviations: BMI, body mass index; MFW_{EEI}, metabolic food waste corresponding to excess energy intake; MFW_{EBF}, metabolic food waste corresponding to excess body fat; NW, normal weight; OB, obese or obesity; OW, overweight.

* Corresponding author.
E-mail addresses: niina.sundin@slu.se (N. Sundin), magdalena.rosell@ki.se (M. Rosell), mattias.eriksson@slu.se (M. Eriksson), carl.jensen@ri.se (C. Jensen), marta.angela.bianchi@ri.se (M. Bianchi).

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Parliament, 2017).

In low-income countries, food is typically lost in the early and middle stages of the food supply chain, while in middle- and high-income countries most food waste occurs once food reaches the consumer (Gustavsson et al., 2011). Sweden is no exception, with high losses reported from retail, food services and households (Brancoli et al., 2019; Eriksson et al., 2020; 2017; 2014; Malefors et al., 2019; Swedish Environmental Protection Agency, 2020). In 2018, more than 0.9 Mt of the 1.3 Mt of food waste generated in Sweden came from households according to the Swedish Environmental Protection Agency (2020). In this case, food waste generated throughout the food value chain from primary production to households was included, and the household food waste contained both food waste, and food and drinks discarded in the drain. Further, 430 kt was considered avoidable, such as food scraps and shriveled or moldy fruit and vegetables, accounting for approximately 920 kt CO_2e in annual GHGEs (Swedish Food Agency, 2016).

Even in countries like Sweden with advanced waste management systems emphasizing resource recovery, only a small fraction of resources invested in food production can be recovered from food waste (Brancoli et al., 2020; Eriksson et al., 2015; Eriksson and Spångberg, 2017). Due to the extent of the unnecessary waste of resources, the food waste issue has become increasingly part of the public agenda. As a global example, target 12.3 for reduction of global food loss and waste is included in The 2030 Agenda for Sustainable Development by the United Nations (UN, 2015). Furthermore, food waste has become a priority for action at both European Union and national levels, including Sweden (European Commission, 2016; Swedish Food Agency et al., 2018).

Modern food systems also contribute to various diet-related diseases, which is another aspect of their unsustainability. Food systems are failing to supply optimal nutrition to everyone, resulting in widespread malnutrition throughout the globe, in wealthy and poor nations alike (WHO, 2020a). Although global food production is sufficient to meet the energy requirements of the global population, 820 million people are still undernourished due to lack of access to food, while nearly 2 billion people have overweight (OW) or obesity (OB) (FAO et al., 2020; WHO, 2020b). OB has become one of the major global health challenges of our time with an estimated cost of US$2 trillion annually (Dobbs et al., 2014; Lehnert et al., 2013). In fact, during the last four decades, the worldwide prevalence of obesity has nearly tripled and is continuing to rise (WHO, 2020a). Moreover, the prevalence of OW and OB among children aged 5–19 has undergone a dramatic rise from just 4 to over 18% during the same time period (Di Cesare et al., 2019). OW and OB, once considered an issue of high-income countries only, is now on the rise in low- and middle-income countries as well affecting every region of the world (WHO, 2020a). Even in high-income countries like Sweden, undernourishment can still be a problem due to food poverty (Bergström et al., 2020), while malnutrition usually comes in the form of overnutrition and poor nutrient balance, leading to high rates of OW and OB. In particular, high consumption of junk foods that are high in sugar, salt, and fat is an established risk factor not only for OW and OB but also for diet-related non-communicable diseases, such as cardiovascular disease (WHO, 2018a, 2020b). In Sweden, 51% of the adult population have now OW or OB and non-communicable diseases are responsible for 90% of all deaths, representing an enormous socioeconomic cost to society (Public Health Agency of Sweden, 2020a; WHO, 2018b; European Commission, 2020).

Excess food intake is considered the fundamental cause of OW and OB (WHO, 2020b). Excess food intake occurs when energy intake exceeds the body's physiological needs, leading to a positive imbalance between energy intake and energy expenditure. The negative health consequences of excess food intake are well acknowledged as a global issue, but the environmental implications of excess food intake have been less well studied. In one study, excess food intake in the American population was estimated as average excess energy intake of 400 kcal/person/day, suggesting an increase in associated environmental impacts due to increased land use, soil loss, energy expenditure, and pollution (Blair and Sobal, 2006). Another study suggested that OB is responsible for higher GHGEs through increased fuel usage, additional food production, and higher amounts of organic waste (Michaelowa and Dransfeld, 2008). Lastly, one study estimated a 19% increase in energy intake required to maintain the basal metabolic rate, corresponding to 300 kt CO_2e per year, by the British population with a hypothetical 40% OB rate (Edwards and Roberts, 2009).

Although excess food intake is seldom included in food system models, studies are emerging where excess food intake is regarded as waste (Porter and Reay, 2016). These studies point to the fact that system losses from excess food intake can be as high as consumer food waste, with similar food security and sustainability implications (Alexander et al., 2017). Others argue that food eaten above physiological needs should be considered waste, and introduce the notion of metabolic food waste as a result of excess body fat accumulated in the population (Serafini and Toti, 2016; Toti et al., 2019).

Estimating the environmental impact of metabolic food waste is a relatively new area of research, and the few studies published so far have also used different methods. To our knowledge, no previous attempt has been made to estimate the amount of metabolic food waste or its climate impact in Sweden. Therefore, the main aim of the present study was to estimate the climate impact of metabolic food waste among the adult population in Sweden, according to three diet scenarios. An additional aim was to apply and compare two methods for quantification of metabolic food waste, based on: a) the energy content of excess body fat, and b) excess energy intake due to excess body fat, in order to find the best-suited method for calculating metabolic food waste.

2. Methods

Excess body fat and excess energy intake were calculated based on the national OW and OB prevalence statistics for the adult population (16 years of age and above) in Sweden (SCB, 2019). The caloric amounts of excess body fat and excess energy intake were converted to metabolic food waste, applying the average results of the latest national adult dietary survey according to three different food intake scenarios (Amcoff et al., 2012). The carbon footprints of metabolic food waste corresponding to excess body fat (MFW_{EBF}) and metabolic food waste corresponding to excess energy intake (MFW_{EEI}) were then derived from the RISE Food Climate Database (version 1.6) (Florén et al., 2017).

2.1. Calculations of excess body fat

Calculations of excess body fat were conducted for each body mass index (BMI) group (normal weight (NW), OW, and OB), for females and males, respectively, prior to averaging them, according to the following steps and based on the assumption that energy balance existed in the whole population:

1) Average body weight was calculated based on average BMI and average height as an inverse function of BMI as:

$$average\ body\ weight\ (kg) = midpoint\ of\ BMI\ cut\ off \times average\ height(m)^2 \quad (1)$$

BMI cut-offs for NW, OW, and OB as defined by WHO (2020b) were used. The midpoints of the cut-offs for the populations with NW (21.8) and OW (27.5) were used as the average BMI for the respective populations. For populations with OB, a statistical average of 33.8 was used, sourced from Statistics Sweden (C Samuelsson, personal communication, 10 Feb 2020).

1) The excess body fat of the population with OW was calculated as the difference in average body weight between the populations with OW and NW as:

$$excess\ body\ fat_{OW} = average\ body\ weight_{OW} - average\ body\ weight_{NW} \tag{2}$$

2) The excess body fat of the population with OB was calculated as the difference between the populations with OB and NW as:

$$excess\ body\ fat_{\ OB} = average\ body\ weight_{OB} - \ average\ body\ weight_{NW} \tag{3}$$

3) The excess body fat value obtained, in kg/person, was converted to kcal/person by multiplying by 7778 kcal/kg, corresponding to the energy content of 1 kg body fat (Gibson, 2005).

2.2. Calculation of excess energy intake

Calculations of excess energy intake were conducted for each BMI group and age group, for females and males respectively, prior to averaging them, according to the following steps:

1) Average body weight was calculated based on the average BMI and average height as an inverse function of BMI, using Eq. (1).
2) The average body weight values obtained for females and males, respectively, were inserted into Henry's equation for the respective age groups (Henry, 2005) in order to calculate the average resting energy expenditure. If the age group of the statistical data did not fully match the age groups in Henry's equations, the closest matching alternative was used, e.g., for age group 25–34 Henry's equation for age group 18–29.9 was applied.
3) The resting energy expenditure value was multiplied by the average physical activity level of Swedish adults of 1.6 (Nordic Council of Ministers, 2014), in order to calculate the average total energy expenditure as:

$$total\ energy\ expenditure = resting\ energy\ expenditure \times physical\ activity\ level \tag{4}$$

4) The excess energy intake for the population with OW was calculated as the difference between the average total energy expenditure of the populations with NW and OW as:

$$excess\ energy\ intake_{\ OW} = total\ energy\ expenditure_{OW} - total\ energy\ expenditure_{NW} \tag{5}$$

5) The excess energy intake for the population with OB was calculated as the difference between the average total energy expenditure of the populations with NW and OB as:

$$excess\ energy\ intake_{\ OB} = total\ energy\ expenditure_{\ OB} - total\ energy\ expenditure_{\ NW} \tag{6}$$

6) The excess energy intake results (kcal/person/day) were multiplied by 365 to convert them to annual amounts.

2.3. Calculation of metabolic food waste

To convert excess body fat (kcal per person) and excess energy intake (kcal per person per year) into foods, i.e., metabolic food waste, the latest national dietary survey, *Riksmaten adults 2010–11*, was used (Amcoff et al., 2012). The aim of the survey was to examine food consumption and nutrient intake among women and men in Sweden. This survey was based on a representative sample of 1797 subjects aged 18–80 years. The participants were asked to report everything they ate and drank during four consecutive days using a validated web-based food record diary (Nybacka et al., 2016a, 2016b). The web-based diary was linked to the food composition database held at the National Food Agency including over 1900 food items and dishes reflecting the local food supply at retail. Composite dishes were divided based on their constituent ingredients, which were distributed to their respective food groups. From the data, average intake of energy and foods was retrieved for men and women, respectively. Foods were retrieved according to the predefined food groups as reported in *Riksmaten*. Data on average percent of energy (E%) for different food groups were not available for men and women separately, but only for the whole population. Based on the data, three different excess food intake scenarios were designed.

In the first scenario, it was assumed that the excess food intake in the population with OW and OB represented excess intake of the average Swedish diet. Thus, the assumption was that the excess food intake followed the average food intake pattern, but in a larger amount. This scenario was therefore named *Swedish average food intake* and consisted of all food groups and items as reported in *Riksmaten* (Table 1).

The second scenario, *Swedish modified food intake*, was intended to represent the food intake of adults with BMI above 25 as reported in *Riksmaten*. However, this diet did not differ significantly from the *Swedish average food intake* scenario, which may be explained by misreporting by this group (Amcoff et al., 2012). Therefore, the modified scenario was further developed by removing fruit, vegetables, coffee, and tea (Table 1). Intake of fruit and vegetables was already below the national recommendation of 500 g/day (Amcoff et al., 2012), so it was considered justified not to consider any part of the fruit and vegetable intake as metabolic food waste. In addition, fruit, vegetables, coffee, and tea were considered not to contribute to OW, due to their low energy content. The excess energy content of the excluded fruits and vegetables was proportionally distributed among the food items that remained in this scenario.

The third scenario, *Swedish junk food intake*, was based on the average intake of sweets, snacks, and soda only, as reported in *Riksmaten* for the general adult population (Table 1).

To calculate metabolic food waste, the average excess caloric amounts, corresponding to excess body fat and excess energy intake, were proportionally distributed among the food items included in the three diet scenarios. As a result, MFW_{EBF} in kg of food, and MFW_{EEI} in kg of food per year, could be calculated.

2.4. Calculation of the climate impact of metabolic food waste

To estimate the climate impact of the excess food intake, metabolic food waste food items were first adjusted for the average food retail and consumption waste percentages (FW%), available from the Food and Agricultural Organization (FAO) (Gustavsson et al., 2011) (Table 1). For a detailed description of how FW% was derived for the foods in the three scenarios, see Table S1 in Supplementary Material. The climate impact of MFW_{EBF} and MFW_{EEI} was derived from the RISE Food Climate Database (Florén et al., 2017), which aims to be representative of Swedish food consumption and reflects the dominant production methods used to produce food for the Swedish market. The database is a collection of carbon footprints from LCA assessments from multiple sources performed both in Sweden and internationally. The database is yearly updated, and the version used in this study includes studies up to October 2019 (RISE, 2019). The database has been recently applied in studies where the nutritional quality of foods and diets has been related to their climate impact (Strid et al., 2021a, 2021b; Mehlig et al., 2020). For more information on the climate data used in this study, see Supplementary Material 2. The climate impact was expressed as kg CO_2e per

Table 1
Dietary scenarios describing food intake patterns associated with excess energy intake.

Swedish average food intake			Swedish modified food intake			Swedish junk food intake		
Food Item	MFW $_{EEI}$ (kg/person/year)	MFW $_{EEI}$ adjusted * (kg/person/year)	Food Item	MFW $_{EEI}$ (kg/person/year)	MFW $_{EEI}$ adjusted* (kg/person/year)	Food Item	MFW $_{EEI}$ (kg/person/year)	MFW $_{EEI}$ adjusted* (kg/person/year)
Fruit and vegetables	24.2	32.8	Potatoes	9.8	12.7	Jam, marmalade	5.6	6.4
Potatoes	9.0	11.7	Cereals	16.7	22.7	Crisps, popcorn	2.0	2.2
Cereals	16.3	22.1	Meat, fish, eggs	15.5	18.2	Nuts, seeds	2.4	2.7
Meat, fish, eggs	14.2	16.8	Dairy	24.6	26.6	Ice cream	4.5	4.9
Dairy	23.6	25.5	Added fats	1.0	1.1	Candy & chocolate	6.1	6.9
Added fats	1.0	1.1	Drinks (incl. alcohol; excl. coffee, tea)	21.0	21.4	Buns, cakes	17.5	23.7
Drinks (incl. alcohol)	58.4	78.0	Sweets, snacks and soda	18.2	20.2	Sweet soups & sauces	5.9	6.7
Sweets, snacks and soda	17.0	18.9	Other	9.8	11.1	Desserts	3.3	4.5
Other	8.9	10.1				Sugar, syrup, honey, sweeteners	1.4	1.6
						Juice, soda, cider	49.3	50.6
						Light: juice, soda, cider	15.4	15.8

* MWF is adjusted for food-specific retail and consumer food waste percentages.

kg food product and included all significant GHGEs from primary production up to industrial processing excluding packaging, and excluding also emissions from land-use change, even though these emissions in certain cases can have a major impact, as illustrated by Eriksson et al. (2018).

The carbon footprint was calculated for the food groups and items following the food categorization as reported in *Riksmaten*. Where food items corresponded to broad food groups (i.e., fish and seafood), their climate impact was derived as consumption-weighted averages of the GHGE from specific foods (i.e., salmon, shrimp, etc.) based on national consumption patterns (Swedish Board of Agriculture, 2018; Ziegler and Bergman, 2017). If consumption statistics were not available for certain food items, the climate impact of the corresponding food group was derived as non-weighted averages. When LCA data were missing, climate data were estimated, modeled, or calculated by RISE personnel (i.e. alcoholic beverages with different alcohol percentages). For more detailed composition and aggregation of the food groups, see Table S2 in Supplementary Material. Further, climate impact data referred to the edible part of foods in the prepared form. As *Riksmaten* does not provide information on whether the foods are cooked or non-cooked, it was assumed that: a) the climate data for vegetables, fruit, and berries were calculated based on non-cooked foodstuffs; b) the climate data for potatoes, rice, pasta, meat, poultry, fish, seafood, and eggs were calculated based on cooked foodstuffs; and c) since there can be different preparation methods for the same foodstuff, the carbon footprint corresponding to the most common cooking methods was used. Lastly, the GHGEs of metabolic food waste were calculated by multiplying the amounts of metabolic food waste by the carbon footprint for each food item.

3. Results

3.1. Excess body fat and excess energy intake in the Swedish adult population

The average excess body fat was 17 and 36 kg per person for the Swedish adult population with OW and OB respectively, corresponding to 135 000 and 279 000 excess kcal per person (Table 2). On a population level, excess body fat amounted to 93 kt in total, corresponding to 727 billion kcal for the Swedish adult population with OW and OB in 2018. Furthermore, the average excess energy intake was 131 000 and 265 000 kcal per person and year for the Swedish adult population with OW and OB, respectively (Table 2). On a population level, excess energy intake amounted to 699 billion kcal per year as a total for the Swedish adult population with OW and OB in 2018.

Table 2
Excess body fat (EBF) and excess energy intake (EEI) of the Swedish adult population with overweight (OW) and obesity (OB) in 2018.

		OW	OB
Gender (M/F)*	million people	1.74 / 1.22	0.6 / 0.57
EBF	kg/person	17	36
EBF	kcal/person	135 000	279 000
EEI	kcal/person/y	131 000	265 000

* Source: Statistics Sweden (SCB), 2019.

3.2. Metabolic food waste

The values of MFW_{EBF} and MFW_{EEI} were similar in magnitude, although it should be noted that their units differ (Fig. 1). Further, the metabolic food waste results varied to some extent depending on the food intake scenario. The *Swedish average food intake* scenario resulted in the largest amounts of both MFW_{EBF} and MFW_{EEI}. In comparison, the results of the *Swedish modified food intake* and *Swedish junk food intake* scenarios were both approximately 33% lower, but similar to each other.

Food groups contributing most to metabolic food waste also varied depending on the food intake scenario. Due to the similarity of the results for MFW_{EBF} and MFW_{EEI}, the food groups are only presented for MFW_{EEI} (Fig. 2). For the *Swedish average food intake* scenario, MFW_{EBF} amounted to 180 kg per person and 743 kt of food as a total for the Swedish adult population. For MFW_{EEI}, the amounts were 173 kg per person and year and 713 kt of food per year in total. The food groups contributing most to MFW_{EEI} were, in descending order: 1) *drinks including alcoholic beverages*; 2) *fruit and vegetables;* and 3) *dairy products* (Fig. 2). For the *Swedish modified food intake* scenario, MFW_{EBF} amounted to 120 kg per person and 497 kt of food in total for the Swedish adult population. MFW_{EEI} was 117 kg per person and year and 481 kt of food per year in total. The food groups contributing most to MFW_{EEI} were, in descending order: 1) *dairy products*; 2) *drinks (including alcohol but*

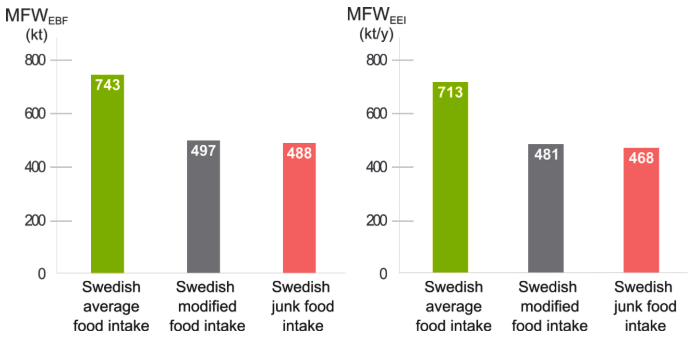

Fig. 1. Total amounts of metabolic food waste corresponding to excess body fat (MFW_{EBF}) (kt) and excess energy intake (MFW_{EEI}) (kt/y) per food intake scenario.

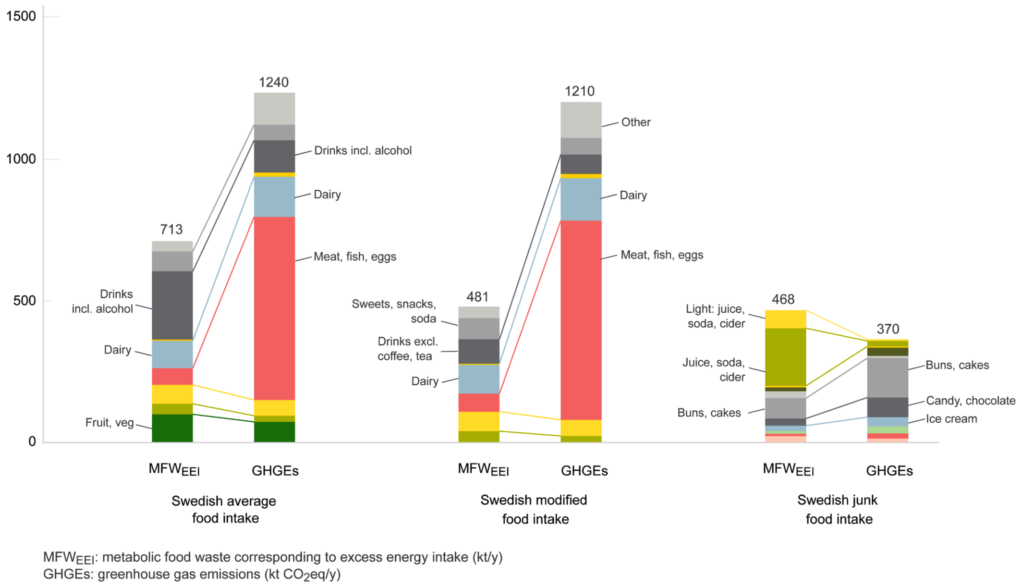

Fig. 2. Annual amount of metabolic food waste corresponding to excess energy intake (MFW_{EEI}) and its climate impact by three food intake scenarios. The results are illustrated by aggregated food groups, where the three food groups contributing most to the results in each scenario are indicated.

excluding coffee and tea); and 3) *sweets, snacks, and soda* (Fig. 2). For the *Swedish junk food intake* scenario, consisting of sweets, snacks, and soda only, MFW_{EBF} amounted to 118 kg per person and 488 kt of food in total for the Swedish adult population, while MFW_{EEI} was 113 kg per person and year and 468 kt of food per year in total. The food groups contributing most to MFW_{EEI} were, in descending order: 1) *juice, soda, and cider*; 2) *buns and cakes*; and 3) *light juice, soda & cider* (Fig. 2).

3.3. Climate impact of metabolic food waste

The climate impact results are presented based only on MFW_{EEI}, due to the similarity of the results for MFW_{EEI} and MFW_{EBF} (Fig. 2). The magnitude of the climate impact based on MFW_{EEI} did not always reflect the amount of MFW_{EEI} when comparing the three dietary scenarios to each other (Fig. 2). Similarly to metabolic food waste, the *Swedish average food intake* scenario gave the highest results in terms of GHGEs. However, the *Swedish modified food intake* scenario resulted in as high a level of GHGEs as the *Swedish average food intake* scenario, while the *Swedish junk food intake* scenario resulted in the lowest amount of GHGEs. In fact, the GHGEs of the *Swedish modified food intake* scenario exceeded the emissions of the *Swedish junk food intake* scenario by more than three-fold, despite both scenarios resulting in similar quantities in terms of metabolic food waste.

The food groups contributing most to the climate impact in the scenarios varied to some degree, although the largest GHGE contributors were in most cases animal-based food commodities. The *Swedish average food intake* scenario resulted in 1280 kt of CO_2e based on MFW_{EBF} in the Swedish adult population, while the result based on MFW_{EEI} was 1240 kt CO_2e per year. The food groups contributing most to the climate impact were, in descending order: 1) *meat, fish and eggs*; 2) *dairy*; and 3) *drinks* *including alcohol* (Fig. 2). The *Swedish modified food intake* scenario resulted in 1240 kt of CO_2e based on excess body fat, and in 1210 kt of CO_2e per year based on excess energy intake, in the Swedish adult population. The food groups contributing most to the climate impact were, in descending order: 1) *meat, fish, and eggs*; 2) *dairy*; and 3) *other (*e.g. *pizza and pie)* (Fig. 2). The *Swedish junk food intake* scenario resulted in 390 kt of CO_2e based on excess body fat, and in 370 kt of CO_2e per year based on excess energy intake, in the Swedish adult population. The food groups contributing most to the climate impact were, in descending order: 1) *buns and cakes;* 2) *candy and chocolate;* and 3) *ice cream* (Fig. 2).

Lastly, metabolic food waste and its climate impact exceeded the amount of avoidable household food waste and its climate impact in Sweden (Fig. 3). In order to harmonize methodologies while conducting the comparison, the GHGE results in the present study were only adjusted with retail FW%, and not with consumption FW%.

4. Discussion

In the present study, the amount of metabolic food waste and its climate impact in Sweden was assessed by two methods and according to three dietary scenarios. The results indicated that the annual amount of metabolic food waste exceeds the total annual amount of avoidable household food waste by up to 66%, representing a significant amount of food waste among the Swedish adult population due to excess food intake (Swedish Environmental Protection Agency, 2020). These results are in line with those in a previous study, where excess food intake was estimated to be at least as high as consumer food waste globally (Alexander et al., 2017). Assuming that two of the scenarios analyzed, *Swedish average food intake* and *Swedish modified food intake*, are closer representations of the actual excess food intake in Sweden than the *Swedish junk food intake* scenario, the results suggest that the corresponding climate impact accounts for approximately 2% of the annual GHGEs of 55 Mt CO_2e in Sweden (Eurostat, 2020). To put the result into further perspective, food production and consumption in Sweden is estimated to be responsible for 20–25% (or roughly 11–14 Mt CO_2e) of the total annual GHGEs in Sweden (Swedish Environmental Protection Agency, 2020). Hence, the annual excess food intake may account for roughly up to 10% of the food-related GHGEs in Sweden. Furthermore, the total annual climate impact of the aforementioned scenarios exceeds the climate impact of avoidable household food waste in Sweden, although there are minor methodological differences in the calculation. Considering the current efforts aimed at reducing avoidable household food waste in Sweden, the European Union, and globally, in order to reduce GHGEs (European Commission, 2016.; Swedish Food Agency et al., 2018), the present results show that excess food intake is a factor to be considered not only in relation to its negative health consequences, but also in climate change mitigation.

The metabolic food waste results varied depending on the dietary scenario. The *Swedish average food intake* scenario resulted in the largest mass of metabolic food waste, whereas the *Swedish modified food intake* and *Swedish junk food intake* scenarios both resulted in approximately 30% lower metabolic food waste mass. The difference may be explained by the *Swedish average food intake* scenario containing more food groups and items low in energy density, such as coffee, tea, vegetables, and fruit, in comparison with the other two scenarios, where such food items were excluded completely.

In comparison with a similar study by Serafini et al. (2016), the *Swedish modified food intake* scenario, based on similar food intake patterns, resulted in approximately 30% higher MFW_{EBF} mass per person with OW and OB. The difference may again be explained by the differences in energy density between foods included in the dietary intake patterns, as Serafini et al. (2016) reported larger proportions of highly energy-dense foods such as meat, alcohol and added fats, but for example no dairy, which was the largest contributor to metabolic food waste in the *Swedish modified food intake* scenario. A further explanation may be a difference in the prevalence of OW, as the present study reported slightly higher average excess body fat. In summary, the determinants of the amount of metabolic food waste are prevalence of OW and OB and the composition of metabolic food waste, i.e., food intake patterns, which may differ from nation to nation.

Further, the results showed that the climate impact of metabolic food waste varied between the dietary scenarios, an effect largely explained by the degree of animal-based foods, especially from ruminants. Previous studies have shown that production of livestock is associated with high GHGEs, especially in the case of ruminants due to their methane production (Scholz et al., 2015). The *Swedish junk food intake* scenario did not include meat, whereas the *Swedish average food intake* and *Swedish modified food intake* scenarios did, resulting in more than three-fold higher GHGEs. Even in the *Swedish junk food intake* scenario, the foods most contributing to the GHGEs contained dairy ingredients (e.g., buns, chocolate, and ice cream).

Although a reduction in animal-based foods and an increase in plant-based foods is often viewed as a necessity for a shift towards environmentally sustainable diets (Willett et al., 2019), our results suggest that dietary scenarios associated with lower GHGEs, such as the *Swedish junk food intake* scenario, may not necessarily be healthier. In fact, previous

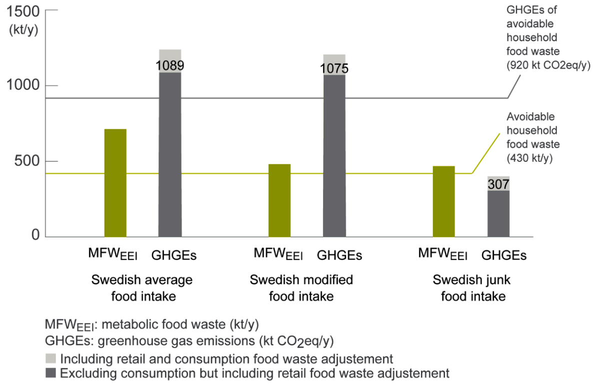

Fig. 3. Metabolic food waste and its climate impact in relation to avoidable household food waste in Sweden. The greenhouse gas emissions (GHGEs) results are presented excluding consumption, but including retail food waste percentage (FW%) adjustment, in order to make the results more comparable to the climate impact of avoidable household food waste. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

reports have highlighted the risk of low climate impact diets being high in sugar (Payne et al., 2016; Vieux et al., 2013). The results of the present study indicate the importance of reducing overall excess food intake for its climate impact, regardless of the composition and quality of foods overeaten, but from a climate perspective a reduction in overconsumption of meat and dairy would be most effective. However, this has to be integrated with the perspective of diet quality since, by definition, sustainable diets not only entail low environmental impact but are also healthy (FAO and WHO, 2019). Therefore, combining both nutritional quality and environmental impact of food choices is fundamental when considering excess food intake.

Previous studies have applied various methods for estimating the caloric value of excess food intake and the foods it comprises. However, to the best of our knowledge, no previous study has attempted to quantify both excess body fat and excess energy intake to estimate climate or any other environmental impact, or to compare the two methods. Although both methods resulted in similarly large quantities of metabolic food waste generated in Sweden, there are some important differences in the methods to be considered. First, the unit of excess body fat is mass, thus revealing no information on how long the body fat has taken to accumulate, which may lead to challenges in interpreting the results. Serafini et al. (2016) suggest addressing this issue by assessing metabolic food waste in epidemiological studies to measure the rise in OB and calculating the environmental impact over time. While this may work, estimates of the climate impact of excess food intake over time could also be based on MFW_{EEI} (Edwards and Roberts, 2009; Porter and Reay, 2016). As the calculation of excess energy intake is based on the extra energy a body requires to maintain existing excess body fat over time (Hall et al., 2011), the unit of MFW_{EEI} is mass/time. Measurements expressed in relation to time are easier to interpret and comparable with other measurements. More importantly, with MFW_{EBF} and MFW_{EEI} measuring different aspects of metabolic food waste, the results of the present study indicate that an amount closely equivalent to the total MFW_{EBF} is generated every year as MFW_{EEI}, risking a considerable annual amount of metabolic food waste going unnoticed if not measured as MFW_{EEI}. Therefore, MFW_{EEI} may be the best-suited method for estimation of metabolic food waste and its environmental impact.

This study suffered from some limitations. Since data on the actual food intake of the adult population with OW and OB in Sweden are lacking, a modeling approach was used to convert the caloric amounts of excess body fat and excess energy intake into metabolic food waste based on three possible dietary scenarios. The dietary scenarios were chosen to represent two opposite alternatives of the excess food intake (Swedish average and Swedish junk food intake), and a more likely scenario in between the two, Swedish modified food intake, following an excess food intake pattern suggested by a previous study (Serafini et al., 2016). The inclusion of the scenarios may be considered as sensitivity analyses of the input data of excess food intake, where especially the climate impact results between the Swedish junk food intake and the other two scenarios differed. Considering that, the excess food intake does not likely consist of junk foods only, but a mixture of all types of energy-dense foods, the results suggest that the true results may lie closer to the Swedish modified food intake. However, since the dietary scenarios were calculated based on the national average food intake of the whole adult population, including people with NW (Amcoff et al., 2012), the proportions of the foods included in the food intake scenario are a further uncertainty requiring caution when interpreting the results.

Further, food-recording methods used in national food surveys often contain limitations per se, such as lack of specific foods (e.g., oils) or poor detail on meal ingredients and preparation methods, which may add to the uncertainty in the data. Moreover, the prevalence statistics of OW and OB were based on self-reported data on body weight and height. Self-reporting of body weight has been associated with under-reporting, especially among subjects with OB, while self-reporting of height has been associated with over-reporting (Gibson, 2005), possibly leading to slightly underestimated excess body fat and excess energy intake in the present study. Further, it has been shown that BMI tends to underestimate rather than overestimate body fatness, which could cause further underestimation of excess body fat and excess energy intake (Okorodudu et al., 2010). Due to lack of data, the same physical activity level value of 1.6 was assumed for all the BMI groups in this study, although there may be differences in physical activity levels between the groups. For example, if the population with OB had a physical activity level of 1.5, the excess energy intake results would be slight overestimates. Considering all these limitations, the results in the present study, especially concerning MFW_{EBF} and its climate impact, could be underestimates. Lastly, it should be noted that the significance of metabolic food waste and its climate impact is underestimated when compared with avoidable household food waste due to household waste amounts including food waste from the entire Swedish population, whereas metabolic food waste is based on the adult population only. Although OW and OB affect a smaller proportion of the child population than of the adult population, its prevalence is increasing in all age groups, children included (Public Health Agency of Sweden 2020a, 2020b). In conclusion, future research based on OW and OB data, and on food intake data for the entire population with OW and OB, is needed to confirm the results of the present study.

Carbon footprints were obtained from a database rather than been ad hoc extracted from the literature for this study. It is therefore important to take into consideration both the heterogeneity of the underlying data and the high variability, which is intrinsic in the LCA methodology (i.e. carbon footprint estimates can be highly variable depending on geography, seasonality, method of production, the energy source for processing, etc.), when analyzing the results from this study. The results should therefore be interpreted as approximate providing an estimate of the magnitude of the climate impact associated with excess food intake, rather than exact. Moreover, the carbon footprints did not include GHGEs related to packaging or homebound transportation of food from grocery stores. While not the major contributors of GHGEs in the food supply chain, the exclusion of the aforementioned emissions could cause a slight underestimation of the results.

The present study included climate as the only environmental impact category when estimating the impact of excess food intake in Sweden. Nevertheless, excess food intake likely also contributes negatively to other environmental impacts, such as depletion of freshwater sources, land-use change, and loss of biodiversity, which could also be estimated by using the methodology of the present study (Crenna et al., 2019; Moberg et al., 2020; Springmann et al., 2018). In addition, while junk foods made a less significant negative contribution to climate impact in the present study, they could make a greater contribution if other environmental impacts were investigated. The use of scarce resources for producing ultra-processed foods with low nutritional value that contribute to OB and ill health seems unjustified in today's world, which is in need of sustainable food systems (Hadjikakou and Bake, 2020).

The results of the present study highlight the magnitude of metabolic food waste and its climate impact as an avoidable environmental burden. Although the results are based on data specific to Sweden, other countries with similar demographics and food cultures are likely to have similar results due to the connection between the amount of metabolic food waste and the prevalence of OW and OB. Additionally, the methodology applied in this study, which for the first time used and compared two different methods to estimate the metabolic food waste, can be replicated in other countries enabling more international studies assessing the environmental impact of excess food intake. The high prevalence of OW and OB is a major global issue, for adults and children alike, and due to the challenges in treating OB, its prevention is of the highest importance (Nittari et al., 2019; Vorkoper et al., 2021; WHO; 1999). However, despite the serious efforts to reverse the OW and OB epidemic for the past three decades, the prevalence is increasing throughout the globe (Swinburn et al., 2019; WHO, 2020b). While reasons for this may be various from a lack of political will to a lack of public interest in solving the issue, OB has also largely been treated in isolation from other global challenges (Lawrence and Friel, 2020; Swinburn et al., 2019). Simultaneously, the urgency of solving the global climate issue is widely recognized, with an increasing amount of mitigation agreements and action plans on all levels (European Commission, 2016; Swedish Food Agency et al., 2018; UNFCCC, 2021). However, excess food intake, or metabolic food waste, is currently not addressed in plans for higher environmental sustainability, such as food waste reduction plans for mitigating climate impact. Yet, linking metabolic food waste together with environmental sustainability and public health as means to support policymaking could come with benefits (Lawrence and Friel, 2020). Combining the issues could be a way not only strengthening the efforts needed in solving them, but also to provide an opportunity for synergies while doing so.

Conclusions

In conclusion, MFW_{EEI} exceeded the total amount of annual avoidable household food waste, indicating a significant amount of continuous food wastage due to the excess food intake in Sweden. Further, the climate impact of the excess food intake accounted for up to 2% of the total and 10% of the food-related annual GHGEs in Sweden, depending on the proportion of animal-based foods. The present study confirms the magnitude of the hidden climate cost of excess food intake and presents a method for estimating its extent that can be applied internationally to further transform food systems. Food systems are dynamic and complex due to their interconnections with other systems, such as economic, social, and political, where changes in one system affect the others. While metabolic food waste only occurs at the consumer stage, its successful reduction due to a collective dietary change would require changes and adaptation throughout the whole food system. Such changes, such as taxation on sugary drinks or re-designed junk food campaigning strategies, have proven challenging in the past as interventions proposed to change food systems for better health and environmental outcomes often receive strong responses from the business and even the public (Swinburn et al., 2019). Environmental or climate implications of such food system transformation were neither captured by the methodology nor included in the scope of the present study and therefore further studies are warranted. Further, as highlighted by the results of the present study, there is a need to prioritize global interventions to reduce excess food intake as a means to benefit both human and planetary health. To achieve the above, joint efforts involving all stakeholders along the food supply chain will be necessary. The awareness that up to 10% of food-related GHGEs in a westernized country like Sweden are avoidable, and the potential that addressing these emissions could have for both global planetary and human health, should further drive the transformation of food systems.

Author contributions

Niina Sundin: Conceptualization, Data curation, Formal analysis, Methodology, Writing – original draft, Writing – review & editing

Magdalena Rosell: Conceptualization, Methodology, Supervision, Writing – review & editing

Mattias Eriksson: Funding acquisition, Writing – review & editing

Carl Jensen: Conceptualization, Writing – review & editing

Marta Bianchi: Conceptualization, Supervision, Writing – review & editing

All authors have read and agreed to the published version of the manuscript.

Declaration of Competing Interest

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

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2021.105777.

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Surplus food donation: Effectiveness, carbon footprint, and rebound effect

Niina Sundin [a,*], Christine Persson Osowski [b], Ingrid Strid [a], Mattias Eriksson [a]

[a] Department of Energy and Technology, Swedish University of Agricultural Sciences, Box 7032, Uppsala 75007, Sweden
[b] Department of Public Health Sciences, Mälardalen University, Sweden

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ABSTRACT

Surplus food redistribution can be a way to relieve co-existing food insecurity and food waste. The food waste hierarchy ranks surplus food donations for human consumption as the next best strategy, when food waste cannot be prevented. However, the effectiveness of food donation in terms of the amount consumed, or food donation as a food waste management measure have rarely been assessed. The few studies conducted to date report substantial environmental savings, but the results may be sensitive to assumptions regarding substituted food. Rebound effects are also not included, but are likely to offset environmental savings from food donation. Therefore, this study investigated the effectiveness, carbon footprint, and rebound effect of a food donation system run by a charity in Sweden, and compared the results with those of anaerobic digestion. Multiple analytical methods were used, including material flow analysis, life cycle assessment, questionnaire, and 24-hour dietary recall. In the life cycle assessment, carbon footprint of substituted products were credited to the overall results using a system expansion. In addition, direct and indirect rebound effects associated with re-spending of substitution-related monetary savings were included. The results revealed a complex but effective network aimed at salvaging as much of the redistributed food as possible, with 78% of redistributed food eaten, but there was also a substantial rebound effect, offsetting 51% of potential carbon emissions savings from food donation. Nonetheless, the net result of food donation was almost twice the climate benefit of anaerobic digestion (-0.40 vs. -0.22 kg CO2e/FU), supporting the food waste hierarchy.

1. Introduction

Food waste has been characterized as a wicked problem, with complex root causes (Minor et al., 2019; Närvänen et al., 2020; Weber and Khademian, 2008). Food waste has now reached unprecedented levels, with roughly one-third of global food produced becoming food loss and waste (FLW), representing a missed opportunity for improved food security and an annual environmental, economic, and social cost of 2.6 trillion USD (FAO, 2014; Gustavsson et al., 2011). In the European Union (EU), food waste represents 20% of food produced, costing 143 billion EUR annually (Stenmarck et al., 2016). Prevention of food waste at source must be the highest priority, but the food waste hierarchy, also adopted in the EU, ranks redistribution of surplus food for human consumption as the next best strategy when food waste cannot be prevented (European Commission, 2020). In reality, however, most food waste is treated by far lower-priority options, such as composting, incineration, or landfill (European Commission, 2020; Eurostat, 2020; Obersteiner et al., 2021).

Surplus food redistribution, i.e., food donation to people in need, can be beneficial for various reasons. Apart from environmental, economic, and social gains, using the food for its intended purpose salvages its energy and nutrient content. In fact, a previous study highlighted the high nutritional value of retail and consumer food waste and pointed to a corresponding nutrient deficit in the average American diet (Spiker et al., 2017). Moreover, surplus food redistribution is increasingly being recognized as a way to relieve food insecurity and food waste issue simultaneously (Schneider, 2013).

Although sufficient food is produced worldwide to meet the needs of the global population, 2 billion people still lack regular access to sufficient food and more than 690 million are hungry (FAO, 2021a). The vast majority of global hunger occurs in low-income countries and the largest share of FLW occurs in middle- and high-income countries, but food insecurity and food waste can coexist within countries and regions (FAO, 2021a; Lawrence and Friel, 2019). In high-income regions such as North America and the European Union, where annual FLW amounts to 168 Mt and 129 Mt, respectively (Caldeira et al., 2019a; CEC, 2017;

* Corresponding author.
E-mail addresses: niina.sundin@slu.se (N. Sundin), christine.persson.osowski@mdh.se (C. Persson Osowski), ingrid.strid@slu.se (I. Strid), mattias.eriksson@slu.se (M. Eriksson).

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FAO, 2019), up to 12% of the population still experiences food insecurity. Even in a welfare state like Sweden, food insecurity is a concern for the 6% of the population with low income, and the income gap and at-risk-of-poverty rate are increasing (Karlsson, 2019; SCB, 2019). Meanwhile, 1.3 Mt of food waste is generated in Sweden annually (Swedish Environmental Protection Agency, 2020).

Hunger and FLW are both issues of global concern and both are included in the United Nation's Sustainable Development Goals (SDG). SDG target 12.3, concerning global FLW, includes a specific target on halving per capita food waste at retail and consumer level by 2030 (United Nations, 2015). The retail level generates the least food waste throughout the food supply chain (UNEP, 2021), but a reduction at that level is still deemed necessary since the farther downstream food waste is generated, the more emissions are generated and the more resources are used, and these are recoverable only to a minor degree (Brancoli et al., 2020; Eriksson et al., 2015; Eriksson and Spångberg, 2017; Reynolds et al., 2020; Schneider et al., 2020). Additionally, the retail sector plays a key role in the food supply chain (Brancoli et al., 2019). According to SDG target 2.1, global hunger must also be eradicated by 2030. While food donation does not have the capacity for solving the issues behind hunger or retail food waste, it could work as a short-term solution to relieve both issues. In fact, less than one-quarter of current global food waste would feed the global hungry (FAO, 2021b).

Food donation has been criticized for shifting responsibility from public to private (Riches, 2018) or for not matching clients' needs (Mourad, 2016). Simultaneously, the inevitability of a certain amount of surplus food and a need for feasible solutions for its redistribution has been acknowledged (Facchini et al., 2018; Priefer et al., 2016). Countries such as the United States and France have already implemented legislation to ensure food redistribution (Condamine, 2020; Schneider, 2013). In the EU, food donation guidelines were adopted in 2017, but the level of implementation differs greatly between member states, with countries such as Italy, France, and Spain in the lead (Deloitte et al., 2020). In Sweden, national guidelines are lacking and food redistribution is still loosely managed and represents only a small fraction of national food waste, although great potential for increased food redistribution has been identified (Deloitte et al., 2020; Hanssen, 2014).

While food donation is widely advocated, ineffectiveness of redistribution may arise due to various barriers, such as short shelf-life of perishable foods or lack of organization (De Boeck et al., 2017; Patel et al., 2021). Some food redistribution initiatives have been evaluated for their effectiveness in terms of mass of food rescued (Hecht and Neff, 2019; Goossens et al., 2019). However, in such evaluations ambiguity may exist as to whether the food was redistributed from retail to charity or from charity to people in need, and whether food waste generated in the redistribution process was included. In fact, the amount eaten is seldom reported, although it essentially indicates the effectiveness of surplus food redistribution (Alexander and Smaje, 2008; Hecht and Neff, 2019).

Life cycle assessment (LCA) is a systematic method enabling environmental assessments of food supply chains related to food production and consumption including food waste generation (Caldeira et al., 2019; Moberg et al., 2020; Sinkko et al., 2019; Sundin et al., 2021). Some previous studies have assessed the environmental value of donated food (Cicatiello et al., 2016; Moggi et al., 2018; Reynolds et al., 2015), but more studies are needed on assessing food donation as food waste management. The majority of such studies have focused on evaluating food waste prevention or less prioritized food waste management options such as incineration, composting, and anaerobic digestion (Bernstad and la Cour Jansen, 2012; Bernstad Saraiva Schott and Andersson, 2015; Salemdeeb et al., 2018, 2017a, 2017b). Some previous studies investigating food donation include a system expansion where emissions related to avoided food production by food donation are credited (Albizzati et al., 2019; Bergström et al., 2020; Damiani et al., 2021; Eriksson et al., 2015, 2014). The substitution method has allowed pinpointing the environmental benefit of food donation contributing to reports with substantial environmental savings. These results, however, may have been sensitive to assumptions made on substituted food due to a lack of data on the type and quantity of food that is actually substituted. Further, rebound effects, i.e. emissions arising from re-spending of accrued savings when receiving donated food have not been included in previous analyses although such effects are likely to arise, offsetting some of the environmental savings from food donation, with possible implications for food waste hierarchy (Hagedorn and Wilts, 2019; Martinez-Sanchez et al., 2016; Redlingshöfer et al., 2020).

Therefore, the aim of the present study was to investigate the effectiveness, i.e. the actual eaten amount, and environmental impact of food donation, including the rebound effect, utilizing dietary survey data to investigate food substitution, and to compare food donation to an alternative food waste management approach, anaerobic digestion.

2. Materials and Methods

In a case study commencing in August 2020 to investigate the effectiveness and environmental impact of food donation, a Swedish non-profit organization, Uppsala City Mission (UCM), was chosen as the case. UCM aims to support people in need living in social and financial vulnerability in Uppsala City, and one of its activities is redistribution of surplus food obtained from local retailers. Food redistribution is operated by two sub-units, a food bag center (since 2018) and a soup kitchen (within the current framework since 2016), that are open from Monday to Friday for approximately 45 weeks of the year. On average, the food bag center had 250 active food bag subscribers in 2020, while 34 new subscribers were welcomed in September 2020 and an additional 55 in March 2021. Subscription for a weekly grocery bag in that year was subject to an income limit of 9290 SEK (~910 EUR) per month, set as the threshold for financial vulnerability by UCM. The membership fee is currently 250 SEK (~25 EUR), entitling subscribers to a weekly food bag for six months. Although UCM is unable to predict the exact type and quantity of foods received, it seeks to ensure that food bags always contain certain foods, such as bread, fruit, vegetables, and dairy products. In 2020, the food bag center redistributed 13,756 food bags, representing approximately 170 metric tonnes (t) of food. The soup kitchen had 12,175 visitors in 2020 and served 12 t of surplus food as breakfast and coffee breaks, 3.2 t as lunches (400 g portions), and 19 t as takeaway meals to people living in social vulnerability and homelessness.

A biogas plant located in Uppsala, Sweden, was used in this study to represent the alternative food waste management scenario (anaerobic digestion). In 2020, the plant treated approximately 48,000 t of food waste, of which almost half originated from households and the other half from the retail and food service sector (Uppsala Vatten, 2021a). The end-products, biogas and biofertilizer, were mainly used as fuel for city buses and in crop cultivation, respectively, in that year (Uppsala Vatten, 2021a).

Although the facilities described above are specific to Uppsala City, central Sweden, they are common in a Swedish and European context, making the results generalizable outside the specific case study.

2.1. Material flow analysis

Material flow analysis (MFA) was conducted for the food donation scenario, comprising the surplus food flow from retail gate via charity organization to people in need, based on process mapping of surplus food redistribution activities (Fig. 1). Apart from following surplus food flows from one stakeholder to another, transport of food and occasions when food waste occurred were included in process mapping.

2.1.1. Surplus food flows including pre-consumer waste

The input of surplus food to the system was calculated based on data obtained from UCM. In the study period (2020), the soup kitchen reported having received 28.6 t of surplus food from retail and 16 t from the food bag center, while the food bag center reported that 170 t

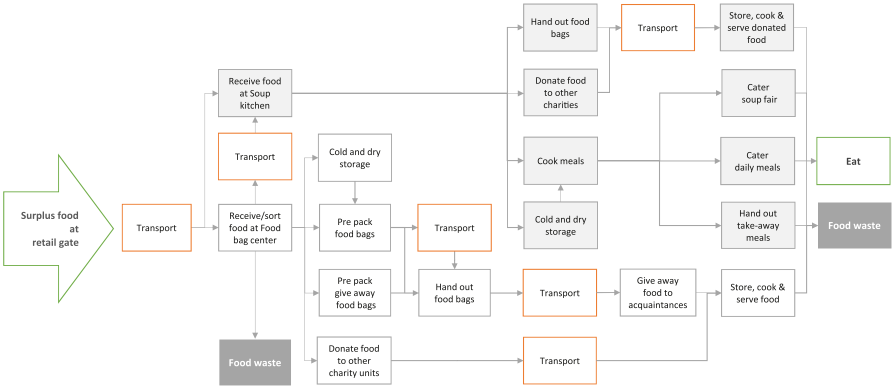

Fig. 1. Process map of the main activities in surplus food flow from retail gate to charity organization units (food bag center and soup kitchen), and then on to people in need.

surplus food were allocated to food bags and 7.8 t to other charity units. The food bag center used a scale and a barcode scanner to record the net weight of food handled, while the soup kitchen logged the weight manually into its computer system. The recorded weights included inedible components. Moreover, 4 t of give-away food bags was assumed for 2020, based on an estimated 85 kg of food per week with such short shelf-life that it was not good enough for any other purpose and not logged onto any system.

As part of the present study, daily food waste measurements (kg) were conducted at the food bag center between August 17, 2020 and April 9, 2021. The average daily amount of food waste was 48.6 kg (± 28.1), consisting of approximately 2.7% dairy, 1.6% meat, and 95.7% plant-based foods. Based on these statistics, food waste in 2020 was calculated to be 11 t, by multiplying the daily average by 223 days, and added to the total surplus food input.

At the soup kitchen, based on its records, approximately 39 t of surplus food were allocated to catering, 3 t to food bags given to visitors, and 2.9 t to other charities in 2020. Of the catering allocation, the records showed that 19 t were allocated further to daily catering, such as serving breakfast, coffee breaks, and lunch, 19 t to take-away meals, and 1.2 t to an annual soup fair. No measuring of pre-consumer food waste took place at the soup kitchen during 2020, but daily catering was estimated to produce 2 t of food waste annually, a figure that was also assumed for the take-away meals.

2.1.2. *Post-consumer waste*

To assess the amount of food bag waste, food bag subscribers were asked to complete a self-administered questionnaire. Specifically, the subscribers were asked whether they wasted any food from the food bags. If they answered in the affirmative, they were asked to self-estimate the average fraction (%) of their food bag food waste, and the reason for the waste. The results showed that 52% of the respondents did not admit to wasting any food. The most common reason for wasting food was short expiry date or not having time to eat the food before its expiry date (42% of responses), while 35% responded that the wasted food was inedible or of bad quality. Food preferences (not accustomed, not liking, unhealthy, too much of the same) were given as the reason in 23% of the responses. The reported food waste fraction was 9% (± 13%), but with very high variation (2%-60%). A similar figure was assumed for the food bags donated from the soup kitchen. Further, 34% of the respondents reported donating some items from the food bags to their close circle, and 7% reported returning unwanted food items to the food bag center. To assess the inedible fraction of the food bags, composition analysis was conducted. The fraction was found to be 12%, which was then assumed for the total amount of surplus food redistributed except for the cooked meals made by the soup kitchen. The methods used, including the questionnaire and composition analysis, are described in further detail below.

2.1.3. *Self-administered questionnaire*

A self-administered questionnaire investigating various aspects of food donation was distributed to people receiving food donations. Study participants were recruited by staff from among visitors to the food bag center and the soup kitchen in the period August 2020-April 2021. Data were collected from three specific recipient groups: 1) existing food bag subscribers; 2) new food bag subscribers; and 3) vulnerable people visiting the soup kitchen. The inclusion criteria were: i) understanding of Swedish, Arabic, or English, ii) existing food bag subscribers had to be subscribers for the last 30 days and new subscribers must not have received any food bags during the previous 30 days; and iii) soup kitchen participants had to free from the influence of alcohol or drugs, and from physical or mental discomfort, during the interview. In total, 67 existing food bag subscribers, 42 new food bag subscribers, and nine soup kitchen visitor participants were recruited (for demographic details of the participants, see Appendix A). The questionnaire was coded to protect the anonymity of the participants. The participants were informed about the present study both verbally and in writing (Swedish, Arabic, or English). Signed informed consent forms were obtained from all the participants.

2.1.4. *Composition analysis of food bags*

Twelve randomly selected food bags were analyzed in terms of their total net weight, percentages of perishable food items and inedible, spoiled, and edible parts, and estimated retail value (Table 1). Since approximately 66% of the food bag subscriptions were *pork-free*, 15% *omnivorous* (mixed diet), 13% *vegetarian,* and the remaining 6% were *special* (e.g., *gluten-* or *lactose-free*), eight of the 12 bags analyzed bags were *pork-free*, two *omnivorous,* and two *vegetarian*. The food bags were analyzed based on photographs of the contents supplied by staff at the food bag center. Food item weights were recorded based on the net weights stated on the packaging or standard weights found in the literature (KF och ICA provkök, 2000) multiplied by the number of items included in the food bag (Appendix B). The edible and inedible fractions were estimated based on literature values (De Laurentiis et al., 2018; KF och ICA provkök, 2000). The proportion of spoilage was visually assessed in the photographs when possible, and no spoilage was detected.

Table 1
Results of composition analysis on 12 randomly chosen food bags (FB1-FB12).

	Total net weight (g)	Perishable food* fraction (%)	Inedible fraction (%)**	Spoilage fraction (%)	Edible fraction (%)	Retail value*** (SEK)	Sample date
Average (SD)	9834 (1033)	70 (7.4)	12 (2.5)	1 (1.7)	87 (2.1)	197 (34.3)	
Pork-free food bags							
FB2	8 164	86	8	0	92	249	7-Sep-20
FB3	9 310	68	11	0	89	150	7-Apr-21
FB4	11 160	59	13	0	87	204	7-Apr-21
FB7	10 920	65	11	0	89	176	12-Apr-21
FB8	10 660	63	11	0	89	222	12-Apr-21
FB10	9 270	64	13	0	87	194	13-Apr-21
FB11	9 040	70	14	0	86	149	14-Apr-21
FB12	9 205	71	14	0	86	178	14-Apr-21
Omnivorous food bags							
FB1	11 469	76	8	6	86	242	23-Mar-21
FB5	10 335	69	12	0	88	239	9-Apr-21
Vegetarian food bags							
FB6	9 053	68	15	0	85	177	9-Apr-21
FB9	9 420	78	14	0	86	191	13-Apr-21

* Perishable food included fresh fruit, vegetables, dairy, fats, meat and fish.
** FB1 based on self-measured data, otherwise fractions retrieved from De Laurentiis et al. (2018) or KF och ICA provkök (2010).
*** Retail value retrieved from www.willys.se including a 50% discount.

To test the quantification method described above, the composition of food bag *FB1* (Table 1), was quantified by weighing all unpackaged food items (Appendix B). Perishable food items were checked for spoilage by looking, feeling, and/or sniffing them. Fruit and vegetables were separated into parts deemed unfit for consumption, such as peels, skins, and stalks, and parts that were spoiled, which were then weighed and recorded. For bananas, strawberries, and lettuce, the separation of spoiled parts was straightforward, but mushrooms had to be considered 100% inedible due to a foul odor from the package. Although this quality check was subjective, it was considered strict and the identified spoilage was deemed justified. The difference in total net weight between weighted FB1 (11469 g) and the estimation thereof based on photographs (11580 g) was 111g (1%). According to the results, 86% of the net weight of *FB1* consisted of edible foods, 8% consisted of inedible parts, and 6% was inedible due to spoilage.

The composition data were averaged, giving a food bag weighing approximately 9830 g and including 70% perishable food items, such as fruit, vegetables, dairy, meat, fish, or fats, and 30% dry goods. The average inedible food waste fraction was 12% (Table 1).

2.2. Carbon footprint analysis

To assess the environmental impact of food donation in terms of global warming potential (GWP), an attributional life cycle assessment including a system expansion for substituted products according to ISO standards 14040–14044 was conducted. Two scenarios were compared in the LCA, food donation and anaerobic digestion (Fig. 2). Carbon footprint (CF) associated with substituted products was credited to the overall results in each scenario. Direct and indirect rebound effects associated with re-spending of substitution-related monetary savings were included. The functional unit (FU) selected was 1 kg surplus food prepared for transportation at the retail gate.

2.2.1. Carbon footprint of food donation

In the assessment of the food donation scenario, emissions relating to transport, packaging, electricity, and food waste treatment were calculated, including the food bag center and the soup kitchen.

2.2.1.1. Transport. Transport data were obtained from UCM, based on its annual statistics. The food bag center collected roughly 70% of the donated surplus food in a van during daily rounds that also included forwarding food to other UCM units. For these deliveries, covering 12,023 km in 2020, 794 L biodiesel were used. The biodiesel used was assumed to be produced in Sweden, with an environmental impact of 0.454 kg CO_2e/L (Swedish Energy Agency, 2020). The remaining 30% of surplus food was delivered by various donors. Their CF was modeled based on the distance between the donors and the food bag center, delivery frequency, delivery tonnage, type of vehicle, and assuming no dead freight, using the NTMCalc 4.0 Environmental Performance Calculator (NTM, 2021). The soup kitchen's vehicle was driven 11,418

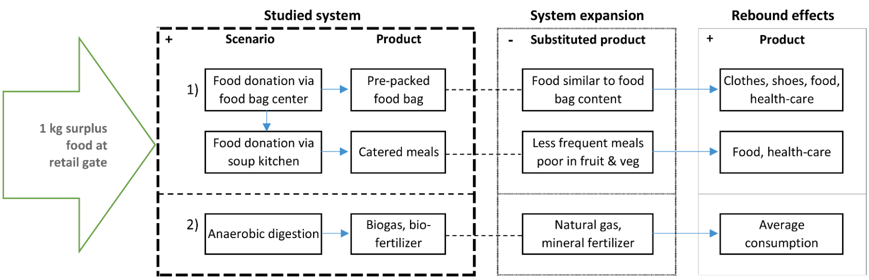

Fig. 2. System diagram illustrating the two scenarios compared, food donation and anaerobic digestion, and their respective products, and a system expansion including substituted products for each scenario and rebound effects associated with product substitutions. For each system, a positive (+) or negative (-) sign indicates the contribution to the net environmental impact of the system.

km in 2020, using 925 L petrol, of which 70% was estimated to be food donation-related driving. The petrol used was assumed to be produced in Sweden, with an environmental impact of 2.92 kg CO_2e/L (Swedish Energy Agency, 2020). The CF of daily food deliveries of 37 kg over 2 km distance by van was modeled assuming no dead freight (NTM, 2021).

The following transport-related data from the questionnaire, which were assumed to be representative of all receivers of food donation were also utilized: 1) place of residence and 2) usual transport method to UCM. According to the results, approximately 50% of the food bag center respondents took the bus, 35% bicycled or walked, and 15% drove a car when picking up their food bags, while 60% of the soup kitchen visitors bicycled or walked, 39% took the bus, and only 1% drove a car. The average return trip by bus amounted to 29.6 km and by car to 14.2 km. The CF for the bus trips was modeled assuming 45% biogas and 55% biodiesel, and 50% passenger occupancy, and that for the car trips assuming petrol and one passenger (NTM, 2021; Wisell et al., 2020).

2.2.1.2. Packaging. In 2020, the food bag center reported using approximately 150 new non-woven polypropylene bags, 100 LDPE plastic bags, and 100 paper bags, the CF of which was estimated based on 0.65, 0.11, and 0.031 kg CO_2e/bag, respectively, including end-of-life management through incineration, (Bisinella et al., 2018). The CF for 2.5 reusable plastic crates (3.279 kg CO_2e/crate) was also included for the food bag center (Tua et al., 2019). For the soup kitchen, the CF of 9500 LPDE freezer bags, 50 LPDE plastic bags, and 25 paper bags per annum was accounted for (Bisinella et al., 2018).

2.2.1.3. Electricity. The food bag center had seven upright freezers, one chest freezer, one small freezer, two fridge-freezers, and two refrigerators. All of these used 100 W/h except for the two fridge-freezers, which used 150 W/h. The compressor run-time was calculated as 12 h/day for all devices except the two refrigerators (8 h/day). The soup kitchen had four upright freezers, three chest freezers, three fridge-freezers, and one refrigerator, for which the values above were assumed. Electricity for one hour of cooking per day was also accounted for, as 1500 W/h. For the electricity, the Nordic electricity mix with an emission factor of 90.4 g CO2e/kWh was assumed (SMED, 2021).

2.2.1.4. Food waste treatment. Since donated surplus food was wasted both at UCM and in recipients' homes, the associated CF of both was included. At home, 47% of food waste was assumed to be sorted correctly and therefore treated by anaerobic digestion, with the remaining part incinerated (Swedish Waste Management, 2016). For UCM, a higher waste sorting rate of 80% was assumed. The CF associated with anaerobic digestion was -0.227 CO_2e/kg (present study). For incineration, the figure was -0.11 kg CO_2e/kg food waste, assuming that food waste consisted of one-third each of banana, lettuce, and bread (Eriksson et al., 2015).

2.2.2. Carbon footprint of anaerobic digestion

Anaerobic digestion was modeled as an alternative waste management scenario where food originating from Uppsala donated to the food bag center (140 t) was instead treated at the biogas plant in Uppsala. In the regional energy plan to cut the CF of domestic transport, increasing local biogas production and its utilization is prioritized (Troeng et al., 2019). Consequently, biogas production has increased continuously in recent years (+38% since 2017), using food waste as substrate and producing biofertilizer as a by-product (Uppsala Vatten, 2021b, 2021a). In this study, transport- and electricity-related CF were accounted for in the anaerobic digestion scenario.

2.2.2.1. Transport. To model transport of food waste to the biogas plant, retailers were first grouped per location, enabling measurement of the pick-up distances as rounds. The pick-ups were assumed to be conducted twice a week, resulting in a total of 6013 km. The plant's trucks consume 0.00012 L/tkm and run on 40% biogas and 60% diesel (I. Vita, personal communication, 23 June 2021). The biodiesel and diesel used were assumed to be produced in Sweden, with an environmental impact of 0.763 and 2.69 kg CO_2e/L, respectively (Swedish Energy Agency, 2020). Transport of biofertilizer was modeled as 30 km distance on rural roads performed by a diesel-run heavy truck with Euro 5 engine assuming 50% load (Eriksson et al., 2015; NTM, 2021).

2.2.2.2. Electricity. The electricity requirement for production of biogas was assumed to be 10 kWh/t of substrate (Eriksson et al., 2015). For CF, the Nordic electricity mix with an emission factor of 90.4 g CO_2e/kWh was assumed (SMED, 2021).

2.2.3. Substitution of food donation

In the food donation scenario, the substitution comprised emissions from foods substituted by food donation (food that was avoided from being purchased and therefore presumed avoided from being produced), excluding food waste. To investigate the food substitution by the food bags, the results of the 24-h dietary recall were analyzed as differences in intake frequencies of food groups between new and existing food bag subscribers. The results indicated similar consumption frequency (70-100% of respondents) for cereals, vegetables, fruit, meat, dairy, spices, beverages, and oils & fats for new and existing subscribers. For potatoes, carrots, red peppers, green leafy vegetables, and fish with lower consumption frequencies (20-50% of respondents), slightly higher frequencies (10-20%) were observed for existing subscribers in comparison with new subscribers. For sweet items, intake frequency was slightly lower for existing compared with new subscribers (50% vs. 60%). Based on the above, it was concluded that the food bags were likely to substitute for food items from the most frequently consumed food groups according to the typical content of the food bags, such as bread, pasta, vegetables, fruit, dairy, and coffee. The CF for the substituted foods was calculated based on the weight fractions of donated foods using cradle to gate CF, including packaging (Röös, 2014) (Appendix B).

To investigate the substituted food by soup kitchen donations, a different type of assessment was conducted because the food donations mainly comprised cooked meals instead of food items. Therefore, for the soup kitchen visitors, the dietary recall results were first analyzed as number of daily meals (including breakfast, lunch, dinner, and snacks). The results suggested that visitors ate 4.5 meals/day when visiting the soup kitchen and 2.3 meals/day when not visiting. Since the soup kitchen served breakfast, lunch, and snacks and provided visitors with take-away meals, i.e., not necessarily covering all the reported 4.5 meals/day, the substitution was based on two meals, amounting to 850 g of food/visitor and day. Based on the dietary data collected, the substituted meals consisted of coffee, bread, dairy, pasta/rice/potato, meat, and some vegetables (Appendix C). The CF of the meals was calculated using cradle to gate CF per food item, including packaging and excluding transport within Sweden, cooking, and waste treatment (Röös, 2014).

2.2.3.1. 24-h dietary recall. To investigate the food intake of receivers of food donation, a single 24-h dietary recall survey was conducted among the study participants using the dietary diversity questionnaire created by FAO (Kennedy, 2011). In total, 55 existing and 36 new food bag subscribers were telephone-interviewed by trained nutritionists. Furthermore, nine soup kitchen visitors were interviewed face-to-face by soup kitchen staff. During the interviews, the participants were asked to recall all food and drink consumed the previous day, including the amounts, and ingredients in the case of composite meals.

2.2.4. Substitution of anaerobic digestion

In the anaerobic digestion scenario, the substituted products were assumed to be natural gas and mineral fertilizer. The biogas produced in

Uppsala is mainly used for running the city's buses, but also some regional buses (Uppsala Vatten, 2021a). However, due to the Covid-19 pandemic, the use of public transportation decreased in 2020, leading to an increase in use of the biogas to produce electricity (Uppsala Vatten, 2021a). Even under normal circumstances, biogas supply and demand may not always match and biogas has to be used for other purposes, or natural gas is required as a buffer to run the buses (Uppsala Vatten, 2021a). While acknowledging the complexity of the energy system, in the scenario it was assumed that the biogas produced was used to run the bus traffic in Uppsala, substituting for natural gas. The yield of the Uppsala biogas plant in 2020 was 0.1 Nm^3 upgraded biogas/kg food waste with an energy content of 9.7 kWh/Nm^3 (L. Nordin, personal communication 24 June 2021). The natural gas emissions replaced were 69.3 g CO_2/MJ, corresponding to the average natural gas consumed in Sweden (Swedish Energy Agency, 2020).

Further, the biofertilizer was used for cultivation, substituting for mineral fertilizer. The substituted production of fertilizer was assumed to use natural gas as an energy source, emitting 2.41 kg CO_2e/kg N (Ahlgren et al., 2010). The amount of fertilizer substituted was based on the average nitrogen content of the average food bag, obtained by dividing the average protein content by a conversion factor of 6.25 (SNFA, 2021). The CF from substituted phosphorus (P) was also calculated, based on an average content of 12.9 g P/kg food (Uppsala Vatten, 2019) and an emission factor of 3.6 kg CO_2e/kg P (Linderholm et al., 2012).

2.2.5. Rebound effect

Rebound effects can arise either from changes in consumption patterns lowering the costs or from efficiency improvements making a service cheaper (Lekve Bjelle et al., 2018). In the context of the present study, rebound effects arise from re-spending of accrued savings due to receiving donated food substituting food that would have otherwise been purchased. The re-spending leads to environmental emissions that are quantified and added to the net carbon footprint results in contrast to emissions corresponding to the substitution that are credited to the net results. The rebound effect is defined as the relationship between potential CF savings (ΔH) and the CF savings not realized (ΔG) (Chitnis et al., 2014; Druckman et al., 2011):(Eqn 1)

$$\textit{Rebound effect} = \frac{\Delta G}{\Delta H} \tag{1}$$

To calculate ΔG, monetary savings associated with substitution, and their re-spending, were investigated for each scenario. The monetary savings were then multiplied by consumption-related GHG intensity (Grabs, 2015) (Appendix D) and added to the CF results of the scenarios.

2.2.5.1. Rebound effect of food donation. For the food donation scenario, the survey results were used to calculate ΔG. The average self-estimated savings of the food bag subscribers were 176 (± 131) SEK/week (17 EUR/week), amounting to 165 SEK/week (16 EUR/week) with the subscription fee deducted. For the soup kitchen visitors, the daily median saving amounted to 25 SEK (± 36) (2 EUR). The savings were mostly spent on clothes or shoes, complementary food, and healthcare (Appendix D).

2.2.5.2. Rebound effect of anaerobic digestion. For the anaerobic digestion scenario, a potential increase in biogas sales profits was assumed. Although aiming at zero financial results, due to being a tax-funded company, surpluses and deficits incur and are settled against prepaid fees of subscribers in the balance sheet. In 2020, the waste operations of the biogas plant as a whole made a deficit of 21 MSEK (2 MEUR), which increased the cost to subscribers to 29.3 MSEK (2.9 MEUR) (Uppsala Vatten, 2021b). Simultaneously, biogas sales resulted in 6.4 MSEK (0.6 MEUR) profit while treating 48,000 t of food waste (Uppsala Vatten, 2021b). Based on these values, treating an extra 237 t of food waste could have increased the biogas sales profits by approximately 30 000 SEK (2900 EUR), which was far too little to settle the existing subscriber debt. However, with no debt, the additional sales profits could have been used to reduce the subscriber fees, resulting in monetary savings for households that were assumed to be spent according to the average Swedish consumption pattern (Grabs, 2015).

3. Results

3.1. Effectiveness of food donation

The proportion of donated food eaten was 78% (185 t), and the proportion wasted was thus 22% (53 t), of the total input of 237 t in 2020 (Fig. 3). The food bag center received 208 t of surplus food, of which 16 t was forwarded to the soup kitchen. Moreover, the soup kitchen received 29 t directly from various retailers, redistributing 45 t of surplus food in total. Upon receipt at the food bag center, surplus food was sorted according to its estimated remaining shelf-life, or disposed of if deemed spoiled (5%). To optimize the system, food with the longest shelf-life was designated for weekly food bags or stored for later use, whereas food close to its expiry was allocated to other charities that could utilize the food shortly or given away as extra to food bag subscribers. Further, 34% of the questionnaire respondents indicated donating part of their food bag content to friends, revealing an additional existing measure to minimize food waste. Similarly, food waste was minimized at the soup kitchen through an allocation to daily catering at the premises, take-away meals, food bags, or other charities. Approximately 12% of the total input via the soup kitchen was estimated to become food waste, while the food waste rate was 25% for the food bag center. Of the total food waste, approximately 28 t (54%) was edible and 24 t (46%) was inedible.

3.2. Carbon footprint

The anaerobic digestion scenario resulted in a carbon-negative net result of -0.22 kg CO_2e/FU. In comparison, the CF of food donation was almost twice that value (-0.40 kg CO_2e/FU) (Fig. 4). These carbon-negative results were largely due to the substitution effects, -0.26 and -0.95 kg CO_2e/FU, respectively. Further, the food donation scenario received minor benefits through credited emissions from the food waste treatment (-0.026 kg CO_2e/FU).

The carbon savings from the food donation scenario were substantially reduced due to the rebound effect of 51%, offsetting 0.50 kg CO_2e/FU. For the anaerobic digestion scenario, the rebound effect was only 2% (0.006 kg CO_2e/FU). Other contributors to the CF were transport-related, including end-user transport for food donation (0.061 kg CO_2e/FU) and transport of bio-fertilizer from the anaerobic digestion plant (0.032 kg CO_2e/FU). Emissions from transport from retail (0.012 kg CO_2e/FU), packaging (0.001 kg CO_2e/FU), and electricity (0.004 kg CO_2e/FU) were only minor contributors to the food donation results. For the anaerobic digestion system, transport from retail (0.001 kg CO_2e/FU) and electricity (0.0009 kg CO_2e/FU) also played only a minor role in the results.

When the soup kitchen and food bag center results were separated, some differences were observed (Fig. 4). While the net result of the soup kitchen was -0.27 kg CO_2e/FU, the food bag center was 55% more carbon-negative, at -0.42 kg CO_2e/FU. The difference was mainly due to a smaller substitution effect of the soup kitchen compared with the food bag center (-0.82 vs. -0.98 kg CO_2e/FU), although transport-related emissions also contributed. Transport emissions from retail, amounting to 0.065 kg CO_2e/FU for the soup kitchen, were higher than transport emissions from the food bag center (0.003 kg CO_2e/FU). End-user transport emissions were also higher for the soup kitchen (0.092 kg CO_2e/FU) than for the food bag center (0.054 CO_2e/FU). Further, due to the higher food waste rate of the food bag center, the amount of emissions credited due to food waste treatment, amounting to -0.03 kg CO_2e/FU, was three-fold the amount (-0.01 CO_2e/FU) from the soup kitchen.

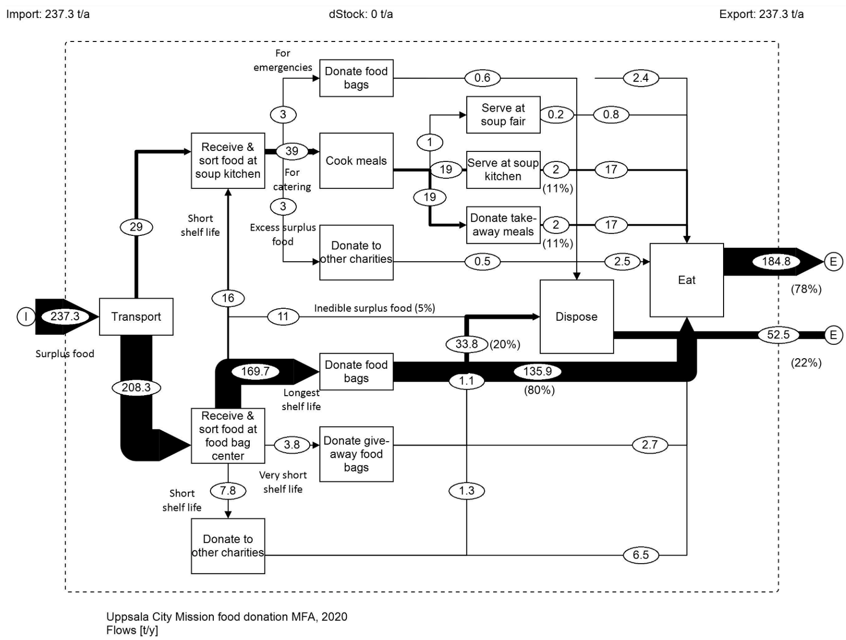

Fig. 3. Material flow diagram of surplus food throughput (237 t in total) via the soup kitchen and food bag center of Uppsala City Mission in 2020. The main flows and various side-flows created in an attempt to minimize food waste within the system are depicted. Approximately 78% (185 t) of the total surplus food flow was eaten, i.e., 22% (53 t) was wasted.

Lastly, the rebound effect was 47% of the potential carbon savings (0.39 kg CO_2e/FU) for the soup kitchen and 52% (0.53 kg CO_2e/FU) for the food bag center.

3.3. Sensitivity analyses

Although transport from retail did not have the greatest influence on the net results, due to an uncertainty related to possible dead freight, in a sensitivity analysis this parameter was tested with 100% return dead freight and max dead freight inbound and outbound (Fig. 5). Moreover, due to the high variation in the survey results utilized for calculating the substitution and rebound effects of food donation, the sensitivity of the most important parameters was tested, including the proportion of substituted meat for the food bags (min 0%; present study 4%; max 10%) and the number of substituted meals (min 1; present study 2; max 4) for the soup kitchen visitors. The following parameters related to the rebound effect were also tested: 1) amount of savings due to receiving donated food (min 0 SEK; present study 165 SEK; max 600 SEK/food bag, and min 0 SEK; present study 25 SEK; max 100 SEK/soup kitchen visit); and 2) spending the savings on the most GHG-intensive consumption category, complementary food (min 0%; present study 20% (food bags) and 43% (soup kitchen); max 100% complementary food). Finally, the effect of changes in the food waste fraction of the food bags was tested (min 2%; present study 9%; max 60%). The results showed low sensitivity to dead freight and food bag food waste fraction, but high sensitivity to the rebound effect-related parameters, potentially resulting in backfire effects, i.e. the rebound effect exceeding 100% (Fig. 5).

4. Discussion

This study investigated the effectiveness, CF, and rebound effect of food donation conducted by a charity organization in Sweden. The results revealed a complex but effective network of processes aimed at salvaging as much of the redistributed food as possible, with a 22% food waste fraction, including household food waste, of the 237 t of surplus food redistributed in 2020. However, there was a substantial rebound effect, offsetting 51% of the potential carbon savings from food donation. Nonetheless, the net effect of food donation was almost twice the climate benefit of anaerobic digestion (-0.40 vs. -0.22 kg CO2e/FU), supporting the food waste hierarchy.

Effectiveness refers to the food waste reduction potential or the degree to which a food waste prevention measure reaches its objective (Caldeira et al., 2019b; Goossens et al., 2019). The indicator total amount of food redistributed, applied for effectiveness in the literature, could cause ambiguity as to whether food waste generated throughout the redistribution process is included (Caldeira et al., 2019b; Hecht and Neff, 2019). Redistribution extending to households, such as food bag donation, also generates additional food waste that is seldom reported. Therefore, rather than just reporting the total amount of food redistributed, the present study investigated its food waste fraction (22%). One previous study estimated that 40% of food donated by retailers in the UK is wasted (Alexander and Smaje, 2008). However, in contrast to the present study, the only outlets for donated food in that study were soup kitchens, explaining some of the difference in the results. The present study revealed a network of outlets utilized by the food bag center and the soup kitchen to salvage surplus food, such as other charity organizations or take-away meals. Further, 34% of the food bag subscribers surveyed in this study reported passing some of the donated

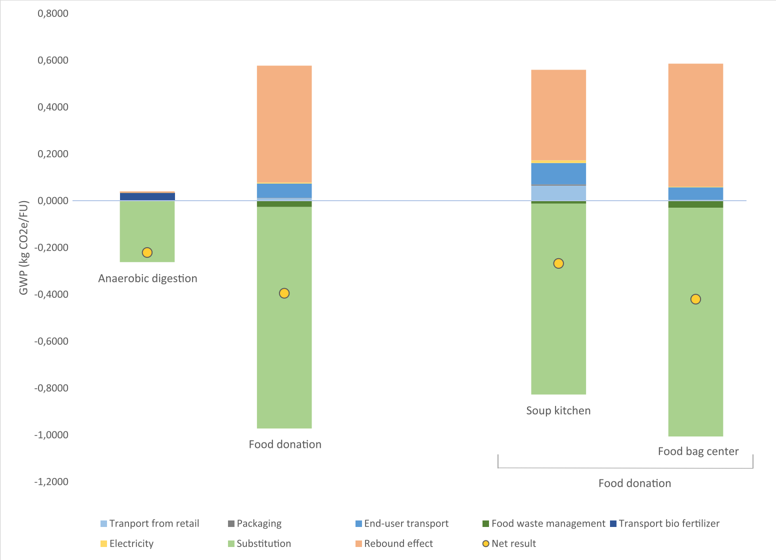

Fig. 4. Carbon footprint of surplus food converted to biogas or donated to charity. The rebound effect for food donation was 51%, offsetting its carbon savings substantially. The two columns to the right give a breakdown of the food donation results for the soup kitchen and food bag center, including a rebound effect of 47% and 52%, respectively.

Fig. 5. Results of sensitivity analysis on net carbon footprint of the food donation scenario, with a breakdown of the results to the soup kitchen and food bag center. The parameters tested relative to the net results of the present study were: no dead freight; 4% meat substitution by food bags; two-meal substitution by soup kitchen; savings of 165 SEK/food bag and 25 SEK/soup kitchen visit; 20% (food bag subscriber) and 43% (soup kitchen visitor) of savings used on complementary food; and 9% food waste fraction of food bags.

food on to their friends to minimize waste. This 'extended network', in combination with the quick food sorting process, ensured high daily turnover of the surplus food, which is essential to minimize waste due to the short shelf-life of surplus food. Despite these efforts, approximately 20% of the food in food bags was wasted (9% edible and 12% inedible food waste). Although this could be seen as shifting food waste along the food supply chain, it could also be a necessary step in order to salvage the rest. While retail has the perspective of disposing/donating food that cannot be sold, charities have the interest of salvaging as much as possible of food that is still edible. Further, while the level of wastage was in line with household food waste fractions reported in the literature (Gustavsson et al., 2011), the main reason differed. The most common reason reported for household food waste, not being used in time, was not the issue for food bag waste, but rather the fact that there was no time to use the food before its expiry, a well-acknowledged barrier to food donation (Caldeira et al., 2019b; Quested and Johnson, 2009). Food wastage in the soup kitchen (11%) was less than previously indicated for the catering sector (20%) (Malefors et al., 2019), which could be due to people in need consuming more of the food served than the average population visiting restaurants and school canteens.

As seen in previous studies, the CF of food donation was strongly influenced by the substitution, resulting in substantial carbon savings (Albizzati et al., 2019; Bergström et al., 2020; Eriksson et al., 2015; Eriksson and Spångberg, 2017). However, in contrast to previous studies, the present assessment included the rebound effects, with the results suggesting that the carbon savings from food donation are less than previously reported. The CF-related rebound effect is a well-studied phenomenon related to energy efficiency improvements (Brockway et al., 2021; Chitnis et al., 2013; Druckman et al., 2011), but has been less well studied in the context of food waste management. Some studies investigating the highest level of the food waste hierarchy, food waste prevention, have reported rebound effects of similar magnitude to those seen in the present study, i.e., 50-106% at consumer level (Albizzati, 2021; Chitnis et al., 2014; Druckman et al., 2011; Hagedorn and Wilts, 2019; Salemdeeb et al., 2017a). As with household food waste prevention, food donation leads to accrued household monetary savings. However, there were some methodological differences influencing the results. First, as shown in the present study, food waste is generated throughout food donation, which should be accounted for, lowering the rebound effect. Further, food substitution may differ between prevention and donation and, as demonstrated by the present study, even between different types of donation. Moreover, in the present study the savings accrued by donated food bags were equivalent to a discounted retail price, instead of the full price, suggesting that food waste prevention can generate larger monetary savings. That in turn could lead to a higher rebound effect, although depending on how the savings are spent. In fact, the rebound effect has been shown to increase with decreasing income, due to the consumption pattern increasing in GHG intensity (Chitnis et al., 2014; Grabs, 2015; Hagedorn and Wilts, 2019), suggesting that food donation can be particularly affected.

The present study also included the rebound effect for the alternative food waste management scenario, anaerobic digestion, which has previously been less well studied. In that scenario, the monetary savings were not accrued due to food waste prevention, but by increasing the amount of food waste treated by anaerobic digestion, based on the assumption that additional biogas sales profits would lead to monetary savings for households in Uppsala City through reduced service fees. The results showed that the rebound effect was significantly lower for anaerobic digestion in comparison with food donation (2% vs. 51%), and dividing the modest savings between thousands of households in Uppsala City made the rebound effect negligible.

A strength of the present study was in investigating both the effectiveness and rebound effect of food donation. The method for assessing the rebound was applied in a similar manner to the substitution, through a system expansion in the LCA, making the assessment holistic, and easy to apply in future studies. Other strengths were the use of primary data related to sensitive parameters (the substitution, monetary savings, and what the savings were spent on) and the use of primary data regarding the food waste fraction and an inedible fraction of the food bags, which reduced data uncertainty. However, there were also some limitations, in particular the fact that the primary data quantifying food waste from the soup kitchen and food bags were non-measured and susceptible to bias. However, based on sensitivity analysis of the food waste parameters, any such bias would not have greatly affected the overall results. Further, the Covid-19 pandemic limited the data collection to some degree resulting in a small sample size of the food bags. Another limitation caused by the pandemic was the low participation rate in the survey and interviews via the soup kitchen, resulting in uncertainty in the data. In sensitivity analysis, parameters related to substitution and rebound effect were found to affect the soup kitchen results, but due to the smaller volume of food redistributed by the soup kitchen, the impact on the overall results was minor.

A further limitation was exclusion of possible climate savings related to land-use change in food substitution by food donation (Albizzati et al., 2019), suggesting that the results could be somewhat underestimated. Moreover, the soup kitchen reported occasionally purchasing food in the past to feed its visitors, when donated food was not available. This substitution effect was also excluded from the present analysis, because prior to the current redistribution set-up the food served was very simple, uncooked, in low amounts, and served to fewer visitors. Since 2016, the food served has been cooked, served regularly, and in larger amounts, extended to take-away meals, and in cases of surpluses even forwarded to other charities, thus serving a larger population of people in need. In addition, the substitution effect of the food bags was investigated based on intake frequencies of food groups instead of intake amounts, which could have led to some misinterpretation of differences in food intake between new and existing food bag subscribers. Further, the CFs of the Food-Climate list (Röös, 2014) are average values for food groups consumed in Sweden, and thus not necessarily representative of the food groups included in donated food. Similarly, the GHG intensities were based on average Swedish consumption (Grabs et al., 2015). Therefore, the substitution and rebound effect results should be interpreted as approximate. Lastly, the anaerobic digestion scenario was modeled with simplified reality, as some retail food waste is incinerated due to being packaged, and should therefore be regarded as the best-case scenario, rather than a reflection of reality.

Despite some wastage, food donation was found to be effective, with 78% of the redistributed food eaten. To achieve this, strategic planning for swift handling of the variable surplus food input with short expiry date was required. The extended network of dedicated donation outlets, including the informal spillover effect into other low-income households, was another key success factor. However, human resources were also required, which could be a vulnerability for an organization relying on volunteers and a barrier in terms of scalability (Berti et al., 2021). To scale up such organizations is likely to require policy support such as the ban to waste food from retail implemented in France (Condamine, 2020). In Sweden, food donation is expected to grow according to the recent dialogue between different stakeholders, but is currently supported by the EU guidelines only while national guidelines are lacking (Swedish Food Agency, 2021). Moreover, to support future policy decisions, a complete sustainability assessment, including the economic and social performance of food donation should also be investigated (Goossens et al., 2019).

Further, mitigating rebound has previously been recommended through policy actions for example by guiding people towards greener or reduced consumption patterns (Druckman et al., 2011; Lekve Bjelle et al., 2018). Considering that low-income groups are associated with a consumption pattern with the highest carbon intensity, strictly from the environmental perspective, such policy work could be of importance when promoting food donation. However, from an equity and ethical point of view, the rebound effect could play an important role as a way to mitigate social issues such as at-risk-of-poverty (Font Vivanco et al., 2016; SCB, 2019). Therefore, such policy work could be focused on limiting the rebound effect from becoming a backfire effect to promote the overall sustainability of food donation. Moreover, food donation aimed at meeting the dietary needs of receivers could reduce their need to purchase complementary food, allowing less carbon-intensive consumption, a strategy worth considering. Interestingly, the results also pointed to the possibility of rebound effects increasing towards the top of the food waste hierarchy, warranting further studies. Overall, while surplus food redistribution cannot address the root causes of food waste or food insecurity, it has a relieving effect and short-term potential for significant contributions to sustainability.

5. Conclusions

Despite some wastage, food donation in the study case was found to be effective, with 78% of 237 t redistributed surplus food eaten, benefiting hundreds of people in need. However, food donation had a substantial rebound effect of 51% (0.50 kg CO_2e/FU), albeit outweighed by the substitution effect (-0.95 kg CO_2e/FU). Despite this rebound effect, food donation resulted in almost twice the climate benefit of anaerobic digestion, supporting the food waste hierarchy. However, strategies for mitigating rebound effects limiting them from becoming backfire effects should be considered when promoting food donation.

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Author Contributions

Niina Sundin: Conceptualization, Data curation, Formal analysis, Methodology, Writing – original draft, Writing – review & editing. Christine Persson Osowski: Conceptualization, Methodology, Supervision, Writing – review & editing. Ingrid Strid: Conceptualization, Methodology, Supervision, Writing – review & editing. Mattias Eriksson: Conceptualization, Funding acquisition, Methodology, Supervision, Writing – review & editing. All authors have read and agreed to the published version of the manuscript.

Declaration of Competing Interest

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

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Appendix A: Demographics of the study participants

	Existing food bag subscribers	New food bag subscribers	Soup kitchen visitors
Number of study participants	67	21	9
Gender, n (%)			
Male:	30 (45)	7 (33)	5 (56)
Female:	37 (55)	14 (67)	4 (44)
Age, mean (SD)	45 (14)	32 (11)	60 (7)
Educational level, n (%)			
Primary School:	13 (19)	6 (43)	5 (56)
Realschule:	9 (13)	1 (7)	0
Lower secondary education:	9 (13)	0	0
Upper secondary education:	4 (6)	4 (29)	0
College or University:	22 (33)	2 (14)	4 (44)
Don't know:	10 (15)	1 (7)	0
Permanent place of living*, n (%)			
Yes:	44 (73)	9 (60)	7 (78)
No:	16 (27)	6 (40)	2 (22)
Number of adults in household, mean (SD)	1.8 (1)	1.4 (0.5)	1 (0)
Number of children in household, mean (SD)	1.7 (2)	1.4 (1.6)	0.1 (0)

Appendix B: Average food bag (FB) content per food group and food item (g/FB), and food bag content per food bag per food item (g)

Food group	Net weight fraction	Food item	Average net weight (g/FB)	kg CO2e/kg food*	Net weight fraction	FB1	FB2	FB3	FB4	FB5	FB6	FB7	FB8	FB9	FB10	FB11	FB12
Cereals	17%	Bread	942	0.80	10%	1 275	560	0	1 000	850	1 048	1 325	1 350	300	1 300	1 300	1 000
		Hard bread	41		0%	0	245	0	0	0	0	0	0	0	245	0	0
		Pasta	292	0.80	3%	500	0	500	500	500	500	500	500	0	0	0	0
		Grains	419	0.60	4%	0	0	2 000	2 000	0	0	0	0	325	700	0	0
White tubers and roots	5%	Potatoes	404	0.10	4%	1 000	750	0	0	0	0	0	0	900	400	900	900
		Crisps	25		0%	0	0	0	0	0	0	0	0	0	0	150	150
		Parsnip	42		0%	0	0	0	0	0	0	500	0	0	0	0	0
Vitamin A rich vegetables and tubers	3%	Sweet peppers (red)	134	1.40	1%	508	125	0	0	0	150	150	150	125	100	150	150
		Carrots	122	0.20	1%	0	264	0	0	0	0	500	0	0	400	150	150
		Sweet potato	13	0.20	0%	0	0	0	150	0	0	0	0	0	0	0	0
Dark green leafy vegetables	9%	Lettuce	365	1.40	4%	528	500	0	0	500	500	500	650	500	500	200	0
		Fennel	21	1.40	0%	0	0	0	0	0	250	0	0	0	0	0	0
		Broccoli	75	0.20	1%	296	0	300	300	0	0	0	0	0	0	0	0
		Kale	17		0%	0	0	0	0	0	0	0	0	200	0	0	0
		Cabbage	278	0.20	3%	0	0	900	930	0	0	0	0	1 500	0	0	0
		Parsley leaves	42		0%	0	0	0	0	0	0	0	0	0	0	250	250
		Eggplant	67	1.40	1%	0	0	0	0	0	0	0	0	0	0	400	400

(continued on next page)

(*continued*)

Food group	Net weight fraction	Food item	Average net weight (g/FB)	kg CO2e/kg food*	Net weight fraction	FB1	FB2	FB3	FB4	FB5	FB6	FB7	FB8	FB9	FB10	FB11	FB12
		Pak choi	25		0%	0	0	0	0	0	0	0	0	0	0	0	300
Other vegetables	11%	Onion	100	0.20	1%	355	0	200	200	125	0	80	240	0	0	0	0
		Zucchini	120	1.40	1%	242	300	0	0	300	0	0	0	300	300	0	0
		Champignon	66	1.40	1%	376	0	0	0	180	0	0	240	0	0	0	0
		Cucumber	109	1.40	1%	0	350	0	0	0	320	320	320	0	0	0	0
		Tomatoes	308	1.40	3%	0	890	480	400	0	0	960	960	0	0	0	0
		Green & yellow pepper	177	1.40	2%	0	500	375	175	200	100	125	250	400	0	0	0
		Beetroot	95	0.20	1%	0	0	425	325	0	0	0	0	0	0	390	0
		Radish	8	0.20	0%	0	0	0	0	100	0	0	0	0	0	0	0
		Corn (conserve)	48		0%	0	0	0	0	285	285	0	0	0	0	0	0
		Chives	3		0%	0	0	0	0	0	0	0	40	0	0	0	0
Vitamin A rich fruit	0%		0		0%	0	0	0	0	0	0	0	0	0	0	0	0
Other fruit and berries	21%	Banana	535	0.60	5%	568	450	750	600	450	600	600	600	300	300	600	600
		Kiwi	31	0.60	0%	123	0	0	0	0	0	0	0	0	0	0	250
		Apple	423	0.60	4%	425	300	600	600	625	575	300	450	300	300	300	300
		Citrus fruits	644	0.60	7%	275	125	575	550	850	1 275	400	575	1 150	875	500	575
		Grapes	75	0.60	1%	0	400	0	500	0	0	0	0	0	0	0	0
		Strawberries	91	11.00	1%	368	0	125	200	200	200	0	0	0	0	0	0
		Avocado	96	0.60	1%	0	0	0	0	200	200	0	0	300	450	0	0
		Dates	33	0.60	0%	0	0	0	0	400	0	0	0	0	0	0	0
		Pear	125	0.60	1%	0	0	0	0	0	0	300	150	0	0	450	600
		Graded coconut	17	0.60	0%	0	0	0	0	0	0	0	0	0	0	200	0
		Blueberries	8	11.00	0%	0	0	0	0	0	0	0	0	0	0	0	100
Organ meat	0%		0		0%	0	0	0	0	0	0	0	0	0	0	0	0
Flesh meats	4%	Charcuterie; mettwurst	173	7.00	2%	1000	0	0	0	1 070	0	0	0	0	0	0	0
		Chicken nuggets	200	3.00	2%	0	0	0	0	0	0	800	800	0	800	0	0
Eggs	0%		0		0%	0	0	0	0	0	0	0	0	0	0	0	0
Fish	0%		13		0%	0	0	0	0	0	0	0	0	160	0	0	0
Legumes, nuts, seeds	1%	Chick peas	19	0.70	0%	230	0	0	0	0	0	0	0	0	0	0	0
		Kidney beans	96	0.70	1%	0	0	230	230	0	0	0	0	230	0	230	230
Dairy	14%	Milk (0.5%)	500	1.00	5%	1000	0	0	0	1 000	0	0	0	0	0	2 000	2 000
		Yoghurt (3%)	433	1.00	4%	1000	0	1 000	1 000	0	0	1 000	1 000	0	200	0	0
		Other	465	2.00	5%	0	250	600	600	1 000	2 000	0	125	1 000	0	0	0
Oils and fats	1%		133	1.50	1%	0	0	0	0	0	0	1 000	600	0	0	0	0
Sweets	4%	Pastries	100	2.00	1%	180	270	0	150	450	0	0	0	150	0	0	0
		Juice	125	0.80	1%	500	0	0	0	0	0	0	0	0	1 000	0	0
		Chocolate	77	2.00	1%	0	100	200	200	100	100	0	0	100	100	20	0
		Candy	128	2.00	1%	0	0	0	0	120	120	400	500	200	200	0	0
		Chewing gum	3	2.00	0%	0	0	0	0	0	0	0	0	0	0	20	20
Spices, condiments and beverages	7%	Tea	38	3.00	0%	50	0	50	50	50	50	50	50	0	0	50	50
		Coffee	346	3.00	4%	0	0	0	500	450	450	450	450	450	500	450	450
		Mineral water	275	0.30	3%	0	0	0	0	330	330	660	660	330	330	330	330
		Cacao	33		0%	0	0	0	0	0	0	0	0	0	0	0	400
Ready-made meals	2%	Sandwiches & wraps (cheese/chicken/shrimp)	117	2.00	1%	190	945	0	0	0	0	0	0	0	270	0	0
		Pastasalad (cheese/ham/chicken)	106	2.00	1%	480	790	0	0	0	0	0	0	0	0	0	0
Other	0%	Yeast	4		0%	0	50	0	0	0	0	0	0	0	0	0	0
		Oatbased cream	17		0%	0	0	0	0	0	0	0	0	200	0	0	0
			9 834			11 469	8 164	9 310	11 160	10 335	9 053	10 920	10 660	9 420	9 270	9 040	9 205

*Carbon footprint used for the calculation of substituted food (Röös, 2014).

Appendix C: Food substitution effect of food donations from the soup kitchen including carbon footprint (CF)

	kg substituted food/person/day	kg CO2e/kg*
Bread	0.06	0.8
Cereals	0.02	0.6
Pasta	0.01	0.8
Rice	0.03	2
Potato	0.04	0.1
Vegetables	0.04	1
Pea Soup	0.07	1
Dairy	0.14	1
Beef	0.06	26
Ham	0.01	7
Sausage	0.02	7
Chicken	0.03	3
Caviar	0.01	3
Margarine	0.00	1.5
Coffee	0.20	3
Buns	0.05	2
Nuts	0.06	1.5
Total	0.85	

*Röös, 2014

Appendix D: Alternative spending of substitution-related monetary savings and greenhouse gas (GHG) intensities

	Expenditure pattern	Expenditure (%)	Expenditure SEK/wk/subscriber	GHG intensity* (kg CO2e/SEK)
Food donation scenario - food bag center	Clothes and shoes	29	48	0.027
	Food	20	33	0.082
	Consumables	17	28	0.03
	Healthcare	16	26	0.018
	Services	7	12	0.008
	Transportation	4	7	0.078
	Housing (rent, energy)	4	7	0.044
	Leisure	1	2	0.027
	Furniture	1	2	0.023
	Restaurant visits	1	2	0.011
	Expenditure pattern	Expenditure (%)	Expenditure SEK/day/visitor	GHG intensity* (kg CO2e/SEK)
Food donation scenario - soup kitchen	Food	43	11	0.082
	Transportation	14	4	0.078
	Healthcare	14	4	0.018
	Housing (rent, energy)	14	4	0.044
	Restaurant visits	14	4	0.011
	Expenditure pattern**	Expenditure** (%)	Expenditure SEK/year***	GHG intensity* (kg CO2e/SEK)
Anaerobic digestion scenario	Housing (rent, energy)	24	7200	0.044
	Transportation	19	5700	0.078
	Leisure	19	5700	0.027
	Food	12	3600	0.082
	Other****	11	3300	0.024
	Clothes and shoes	5	1500	0.027
	Furniture	5	1500	0.023
	Services	5	1500	0.008

*Grabs (2015)
**Expenditure pattern of the average Swedish consumer (Grabs, 2015).
***Collective annual expenditure of the subscribers of the household food waste collection services by Uppsala Vatten.
****Average GHG intensity of expenditures related to beverages, tobacco, consumables and healthcare.

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III

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Sustainability assessment of surplus food donation: A transfer system generating environmental, economic, and social values

Niina Sundin [a,*], Louise Bartek [a], Christine Persson Osowski [b], Ingrid Strid [a], Mattias Eriksson [a]

[a] Department of Energy and Technology, Swedish University of Agricultural Sciences, Box 7032, Uppsala 75007, Sweden
[b] Department of Public Health Sciences, Mälardalen University, Sweden

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Retailers' food waste, often consisting of edible food, could be reduced, while simultaneously tackling food insecurity, through surplus food donations to vulnerable groups. However, sustainability assessments of food donations covering all three sustainability perspectives are scarce, hampering decision-makers in prioritizing donation as a food waste management measure. This Swedish case study assessed the environmental, economic, and social aspects of surplus food donation and examined trade-offs between the different sustainability perspectives. Methods included life cycle assessment, net economic benefit calculation, social life cycle assessment based on food security questionnaires, and nutritional assessments. The results showed that food donation was a way to reduce food waste benefitting the environment and adding economic and social value, to vulnerable people in particular. Despite substantial rebound effects offsetting some potential environmental savings, food bag donations outcompeted anaerobic digestion as a food waste management option in terms of environmental mitigation effect. Regarding trade-offs, accrued savings causing the rebound effects generated important social value for the donation recipients, by relieving their personal finances. Private and public investment was required to fund the donation units, but positive economic value was generated through valorization of surplus food. Food bag donations also showed potential to alleviate recipients' food insecurity and to contribute positively to recipients' nutrition intake. To realize the potential of surplus food donation, policy measures should be better aligned with the waste hierarchy. Despite some trade-offs and inability to solve the underlying problems of food insecurity, food donations have great short-term potential to contribute to a more sustainable society.

1. Introduction

Despite the ambition to halve global food waste set out by United Nations 2030 Agenda for Sustainable Development, unacceptable levels of food continue to be wasted worldwide, while global food insecurity is increasing due to Covid-19, climate change, conflicts, and economic shocks (UNEP, 2021; United Nations, 2022). Consumer wastage is reportedly more pervasive than previously believed, amounting to 930 million tons of food waste globally in 2019 (UNEP, 2021). The vast amounts of food wastage become even more striking, given the increasing number of people living in food insecurity. In 2021, a staggering 2.3 billion people suffered from food insecurity and 828 million people faced hunger globally, a devastating setback to the goal of zero hunger by 2030 (United Nations, 2022).

Access to adequate food is a basic human right (United Nations, 2010). A general assumption is that food insecurity does not exist in high-welfare countries such as Sweden, due to their affluent living standards and social security systems. However, in 2020, 8.6 % of people in the European Union (EU) were unable to afford a proper meal (Eurostat, 2022). In the United Kingdom (UK), 6 % of the population were living in food poverty in 2021 (Francis-Devine et al., 2022). In Sweden, a recent survey showed that 1.9 % of its population did not always have enough food to eat (Borch and Kjærnes, 2016). Increasing at-risk-of-poverty rate and a widening income gap were also reported in 2019 (SCB, 2019). In 2022, increasing food prices and inflation caused an explosive increase in demand for food donations in Sweden (Grönberg, 2022). Meanwhile, a vast amount of food waste is generated in Sweden, both as metabolic food waste, i.e. due to overeating (0.5 million tons/year) (Sundin et al., 2021), and through food discards (1.1 million tons/year) (Hultén et al., 2022). Approximately

* Corresponding author.
E-mail addresses: niina.sundin@slu.se (N. Sundin), louise.bartek@slu.se (L. Bartek), christine.persson.osowski@mdu.se (C. Persson Osowski), ingrid.strid@slu.se (I. Strid), mattias.eriksson@slu.se (M. Eriksson).

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100,000 tons of discarded food waste are generated annually by retail alone (Hultén et al., 2022).

While retailers are responsible for a minor fraction of overall food waste (e.g. 5 % in the EU, 9 % in Sweden), they are considered a key contributor as their food waste consists of unsellable, but often edible, food (Brancoli et al., 2019; Eriksson et al., 2014; Hultén et al., 2022). One way to reduce this type of food waste, and simultaneously tackle food insecurity, is surplus food donation to people in need, which is well-aligned with the waste hierarchy advocated by the EU (European Commission, 2017). According to the waste hierarchy, surplus food redistribution to people in need is the next best option after food waste prevention (where potential surplus food is never produced, thereby saving resources and energy). However, most food waste around the globe is still treated using low-priority options such as incineration (11 %), or landfill and dumping (70 %) (Sabour et al., 2020). There is an increasing trend for retailers to follow the waste hierarchy, prioritizing food waste reduction and redistribution (Huang et al., 2021), but only a fraction of edible surplus food is redistributed. The proportion of donated surplus food within overall food waste was 4 % in the United States (US) in 2021 and 3 % in the UK in 2020 (Feeding America, 2022; WRAP, 2021). In Sweden, the fraction of donated food is even smaller, e.g. 4500 tons or only 0.4 % of overall food waste in 2021 (Lunde Dinesen, personal communication, 2022). The goal in Sweden is to increase the amount of donated surplus food to 10,000 tons/year by 2025 (IVL Svenska Miljöinstitutet, 2022).

Attempts have been made to stimulate food waste management activities, such as surplus food donation, through regulatory and policy measures. Guidelines for food donation were implemented in the EU in 2017, but their execution differs significantly between member states (Deloitte et al., 2020; European Commission, 2017). Fiscal incentives, such as VAT exemptions and tax deductions, are more popular measures. However, Sweden is lagging behind in fiscal incentives and is not aligned with the waste hierarchy, as its political ambition is to further increase anaerobic digestion of waste (Swedish Environmental Protection Agency, 2022). This is a response to the *waste as a resource* narrative in the EU, which has turned attention from waste prevention to renewable energy production technology such as anaerobic digestion (Hultman and Corvellec, 2012). The preference for biogas production over food donation has also been attributed to the framing of food loss and waste as a waste issue in environmental and economic perspectives, but neglecting the social perspective (Johansson, 2021).

Surplus food donations are mainly a focus of food waste prevention policies, and it can thus be assumed that surplus donations are of great benefit. However, only a few studies have evaluated the sustainability impacts of food donations, with the economic and social dimensions, in particular, remaining unscrutinized (Albizzati et al., 2019; Bergström et al., 2020). The aim of the present case study was to bridge this knowledge gap by assessing the environmental, economic, and social aspects of surplus food donation operations located in Uppsala, Sweden, thus providing a holistic view of the various values generated by food donation, including possible trade-offs between the three aspects of sustainability.

2. Literature review

A considerable body of scientific evidence supports a shift toward sustainable food systems for both human and planetary health (Springmann et al., 2018). In efforts to achieve this, halving global food waste is considered key (Willett et al., 2019). Food production is resource-intensive, requiring water, land, energy, labor, and capital, and thus wasting food means wasting these input resources. Food waste accounts for approximately 10 % of global greenhouse gas emissions (GHGE) (WWF-UK, 2021). For example, food that is lost and wasted occupies approximately 30 % of agricultural land area and accounts for 38 % of total energy usage in the global food system (United Nations, 2022). In addition, the most commonly used food waste management, landfill, is a major source of GHGE (Kormi et al., 2018). Food losses and waste also have negative impacts on food security, availability, and affordability, in terms of meeting sufficient caloric needs, sufficient nutrition, and meeting the need for healthy diets for the existing and growing world population (Kufuor et al., 2018). Therefore, the total environmental, economic, and social implications of global food waste come at a tremendous annual cost of 2.6 trillion USD (FAO, 2014).

Studies on the environmental implications of food waste prevention, the highest priority in the waste hierarchy, report significant emission reductions (Redlingshöfer et al., 2020; Obersteiner et al., 2021). The reduction is especially great when waste prevention is compared with lower-priority food waste management options, such as anaerobic digestion, composting, or incineration (Bernstad Saraiva Schott and Andersson, 2015; Oldfield et al., 2016; Eriksson et al., 2015). However, studies assessing the lower-priority options in the waste hierarchy are much more common (Bernstad and la Cour Jansen, 2012; Mondello et al., 2017). Previous research has thus focused on choosing the best food waste treatment method, rather than waste prevention (Redlingshöfer et al., 2020).

In the waste hierarchy, food re-use for human consumption, and re-use for animal feed, lie between prevention and lower hierarchy options such as anaerobic digestion. Salemdeeb et al. (2017b) assessed animal feed in comparison with composting and anaerobic digestion, and confirmed its higher ranking in the waste hierarchy. On assessing the environmental benefits of re-using potato protein side-streams, Bartek et al. (2022) found that producing food instead of feed reduced the environmental impact and caused less damage to ecosystems. Albizzati et al. (2021) found that food waste prevention followed by redistribution was the best valorization pathway to manage food waste. However, similarly to Martinez-Sanchez et al. (2016), they pointed out that the expected environmental benefits may not be realized if economic savings from food waste prevention and redistribution lead to additional consumption that is high in emissions. The trade-offs mediated by rebound effects have been extensively investigated in terms of energy efficiency improvements (Sorrell and Dimitropoulos, 2007). However, only a few studies have considered rebound effects in assessing food waste management options (Albizzati et al., 2022; Sundin et al., 2022), although rebound effects can arise if measures lead to reduced costs for actors in the food chain (Reynolds et al., 2019). Studies investigating household food waste prevention have found substantial rebound effects, ranging between 57 % and 78 % (Hagedorn and Wilts, 2019; Lekve Bjelle et al., 2018; Salemdeeb et al., 2017a).

As in household food waste prevention, rebound effects may arise when redistributing surplus food if recipients of donated food (hereafter simply 'recipients') accrue monetary savings. Rebound effects associated with food donation have been reported to offset 51 % of the potential GHGE savings, although the climate benefit of food donation still outweighs the climate benefit of anaerobic digestion (Sundin et al., 2022). Several studies investigating surplus food donation compared with redistribution initiatives have found that surplus food donations achieve higher GHGE reductions than initiatives such as reprocessing or waste management (Bergström et al., 2020; Eriksson and Spångberg, 2017; Moult et al., 2018). However, those studies did not include rebound effects, which would likely reduce the reported benefits.

The majority of studies to date have focused on GHGE in their environmental assessments, essentially confirming emission savings in the order of the waste hierarchy, but fewer studies have included several environmental impact categories. Brancoli et al. (2020) included 18 impact categories in their investigation of surplus bread donation and concluded that anaerobic digestion and incineration offered the lowest environmental savings, particularly in a low-impact energy system. Similarly, a study comparing food donation to lower hierarchy options concluded that donation generated significant environmental benefits as long as food rescue processes were run efficiently (Damiani et al., 2021). Further, Albizzati et al. (2019) found that anaerobic digestion and incineration were outcompeted in an environmental and economic perspective by surplus food redistribution and use-as-feed.

Sustainability comprises the three-pillar concept of environmental, social, and economic sustainability, also integrated into life cycle assessment (LCA) methodology (Purvis et al., 2019). Complete sustainability assessments, including all three perspectives, on surplus food donation are scarce, as most studies have focused on the environmental or economic aspects (Hecht and Neff, 2019). Further, a standardized approach to sustainability assessment has been lacking (Caldeira et al., 2019). Nevertheless, existing studies suggest promising effects, such as positive return on investment, decreased environmental burden, large quantities of food rescued, and high stakeholder satisfaction (Caldeira et al., 2019; Hecht and Neff, 2019; Reynolds et al., 2015). Among the few complete sustainability assessments conducted on redistribution, Albizzati et al. (2021) found that food waste prevention followed by redistribution was the best pathway to manage food waste across all three pillars of sustainability, whereas Bergström et al. (2020), who compared different redistribution initiatives such as food bag donation and soup kitchens, concluded that these initiatives had different areas of strength in terms of sustainability.

In the literature, social sustainability has received the least attention, although the social benefits of food donation are likely to be of high relevance to recipients in particular. Social impact indicators suggested in the evaluation framework for surplus food redistribution include number of meals donated, jobs created, people learning new skills, and food-insecure people supported (Caldeira et al., 2019). Effects such as community engagement, staff working hours, and volunteer altruism have also been reported (Goossens et al., 2019; Mirosa et al., 2016; Mousa and Freeland-Graves, 2017). However, using social indicators such as these places the focus on society or workers/volunteers, rather than on recipients. Several social impacts of high relevance have been identified for recipients of donated food, such as improved purchasing power, food security, and nutrition (Mousa and Freeland-Graves, 2019a, 2019b; Vittuari et al., 2017; Wolfson and Greeno, 2020), but to date, these type of indicators have rarely been included in social or sustainability assessments of food donation. In addition, recipients as a stakeholder group have rarely been included in economic assessments of food donation activities (Cicatiello et al., 2016; SVA, 2013).

Empirical evidence on the environmental impacts of food waste management options indicate superiority of surplus food donation over lower hierarchy options. However, studies evaluating the sustainability of food donation from all aspects of sustainability and including recipients as a stakeholder group are scarce, hampering decision-makers in prioritizing different measures (Goossens et al., 2019; Vieira et al., 2022). Complete sustainability assessment of surplus food donation would provide a more comprehensive view of its overall impacts, as trade-offs between the three aspects of sustainability are common (UNEP, 2011).

3. Materials and methods

This sustainability assessment on surplus food donation was a case study on the Swedish non-profit organization, Uppsala City Mission (UCM). The operating model of UCM is to redistribute surplus food from retailers to people in need. In addition to supporting vulnerable people while preventing food waste, UCM provides job-training opportunities to people having difficulties entering the labor market. The redistribution operations are funded by donations from private donors, companies, foundations, the local municipality, and the state. The operations are run by a mixture of employed and voluntary labor working in two sub-units, a food bag center and a soup kitchen. The soup kitchen serves cooked meals free of charge to people who are exposed to social vulnerability. The food bag center redistributes weekly food bags for a biannual 250 SEK (~25 EUR) membership fee to recipients whose income must not exceed UCM's threshold for financial vulnerability, 9290 SEK/month (~910 EUR).

To represent an alternative prevalent food waste management in Sweden when investigating the environmental impacts of surplus food donation, a biogas plant located in Uppsala was chosen. This plant treats approximately 48,000 tons of food waste annually to produce biogas and bio fertilizer (Uppsala Vatten, 2021).

Although the facilities included in this case study are located in central Sweden, they are common both in Sweden and in Europe making the case study generalizable to similar, fully operational units beyond the specific location of the case study.

3.1. Life cycle assessment

To assess the environmental impact of food donation, an attributional LCA, where ISO standards 14,040–14,044 were used as guidelines was performed (ISO, 2006a, 2006b). The environmental impacts of three food waste management scenarios, involving food bag donations, soup kitchen donations, and anaerobic digestion, were compared (Fig. 1). In the scenarios, the functional unit (FU) of *1 kg surplus food ready for dispatch at the retail gate* was applied. Further, similarly to Sundin et al. (2022), the environmental impacts associated with substituted products and rebound effects were credited or added to the overall results, respectively.

The system was modelled in SimaPro 9.2 software, using the ReCiPe2016 (H) method for midpoint and endpoint impact assessment (Database & Support team PRé Sustainability, 2021). Datasets from Ecoinvent 3.8 and Agri-footprint 5.0 (mass allocation) representing European conditions were used to describe the system. At the midpoint level, 18 impact categories were assessed. At the endpoint level, 16 of the midpoint impact categories were aggregated to two endpoint categories: 1) Ecosystems, expressed as the loss of species over a certain area and time (species.years) and 2) human health, expressed as disability-adjusted life years (DALYs).

3.1.1. Food waste management scenarios

The three scenarios were modelled as parallel processes with retail gate (surplus food ready for transport) as the starting point. Site location for all scenarios was Uppsala, Sweden, and site-specific input data and inputs were used when possible (see Appendix A). For the food bag and soup kitchen scenarios, the following processes were included: transport to charity, packaging, transport home, food waste treatment, and energy for storage. For anaerobic digestion, the processes included pre-treatment (including transport), and anaerobic digestion.

3.1.2. Substitution

In each of the scenarios, emissions from substituted products were subtracted from the environmental impacts generated by the food waste management scenarios. In the anaerobic digestion scenario, the biogas produced was used to run the bus traffic in Uppsala, thereby substituting for natural gas, and the biofertilizer was used for cultivation, substituting for mineral fertilizer. For more details concerning the input datasets, see Appendix B.

In the food donation scenarios, the substitution involved avoided food purchases and therefore presumed avoided food production, due to receipt of donated food. The substituted food was investigated with the help of a single 24-h dietary recall survey, using FAO's dietary diversity questionnaire (Kennedy et al., 2013), as described in detail in Section 3.3.3, and composition analysis of 30 randomly selected food bags collected in different seasons in 2020–22. The composition analyses were conducted based on photographs of all food items included in the bags. The net weights from packaged food items were used when possible. Further, the number of fruit and vegetables found in the food bags were multiplied by their standard gross weights (KF och ICA provkök, 2000). For a complete list of food groups and items per food bag in grams, see Table C.1 in Appendix C.

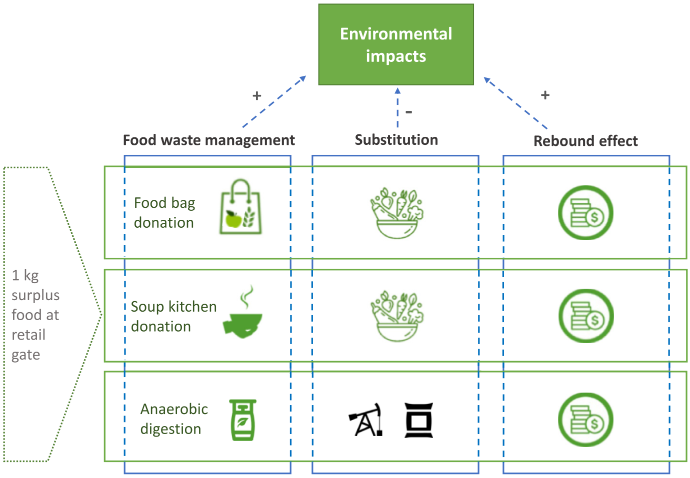

Fig. 1. System boundary diagram illustrating the three scenarios compared, and their respective products. The scenarios included system expansions for substituted products and rebound effects stemming from the substitution. The positive (+) or negative (−) signs demonstrate the nature of the contribution of each sub-system to the overall environmental impacts.

According to the interview results, it was plausible that the food bags substituted for foods from the most frequently consumed food groups according to the average content of the food bags (Fig. 2), as previously observed by Sundin et al. (2022). Expensive *luxury* food items, such as mango, chocolate, and ready-made meals, were excluded, and in total 90 % of food bag weight was assumed to be substituted and 10 % wasted. Substitution of the soup kitchen donations was based on two meals amounting to 850 g food/visitor/day consisting of coffee, bread, dairy, meat, staple foods such as pasta, and some vegetables (Sundin et al., 2022). For more details on the input datasets, see Appendix B.

3.1.3. Rebound effect

The rebound effect refers to reductions in expected benefits from energy efficiency improvements by households because of related behavioral responses in the form of greater energy use (Chitnis et al., 2013). In the present study, a rebound effect was expected to arise from emissions generated by re-spending of accrued savings due to receiving donated food (Sundin et al., 2022) defined as the relationship between potential emission savings (ΔH) and emission savings not realized (ΔG) (Chitnis et al., 2014; Druckman et al., 2011):

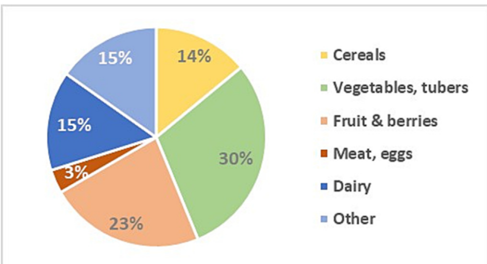

Fig. 2. Average net weight composition (%) of the food bags by food group.

$$\text{Rebound effect} = \frac{\Delta G}{\Delta H} \tag{1}$$

To model ΔG for the food donation scenarios, the monetary savings accrued per food bag received (165 SEK) and per daily soup kitchen visit (25 SEK) were used, together with their associated consumption patterns (Sundin et al., 2022). For the anaerobic digestion scenario, the potential increase in profits from biogas sales (30,000 SEK) was assumed to reduce subscriber fees, resulting in monetary savings for households (Sundin et al., 2022) that were used for the average Swedish consumption pattern (Grabs, 2015). For each consumption category, the rebound-related emissions were modelled per product using the equation:

$$\frac{\text{Accrued savings (SEK)}}{\text{Product price}\left(\frac{SEK}{kg}\right)} \times \text{Product per category}\ (\%) \times \text{Spendings per category}(\%) \tag{2}$$

For a complete list of the consumption categories, datasets, and prices used for the modelling, see Appendix D.

3.2. Economic impact assessment

To assess the economic impact of the food donation scenarios, their net economic benefits were calculated based on the difference in economic benefits created for society through the redistribution activities and the overall cost of these activities (Caldeira et al., 2019). The benefits and costs were investigated from a stakeholder perspective, where the key stakeholders were either accountable for the cost or received the benefit (Fig. 3).

3.2.1. Net economic benefits

The following elements were included in the net benefit calculation: a) the economic value of avoided purchase of food; b) the avoided cost of food waste disposal; and c) the cost of the action (Caldeira et al., 2019). Avoided purchase of food was applied to recipients but not to UCM, as their food donation activities depended on a free supply of surplus food and therefore no purchasing of food was avoided. Due to high

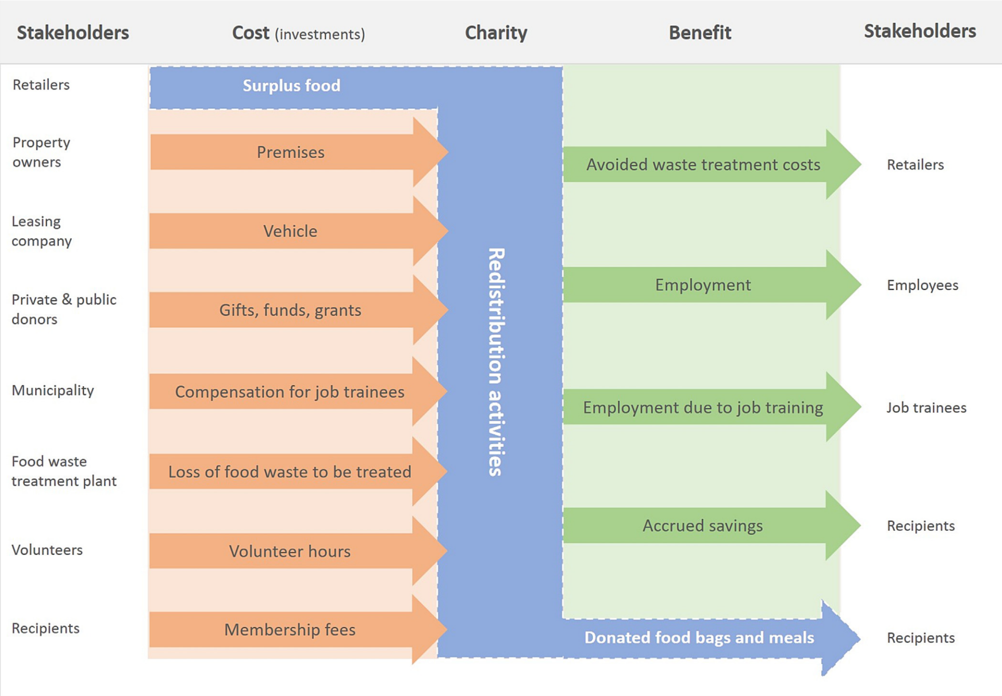

Fig. 3. Illustration of the costs (investments) and benefits associated with surplus food redistribution activities by Uppsala City Mission. The surplus food donated from retail was considered food waste and therefore bore no economic value on entering the system. Through the redistribution activities, enabled by external investments, surplus food was transformed into food bags and cooked meals, creating economic benefits for stakeholders.

labor costs, volunteers are a necessary part of UCM's operating model. UCM also receives compensation from the municipality to employ job trainees in exchange for helping them to overcome employment barriers. Therefore, the societal benefits created through *employment* and *job-training leading to employment* were included as an additional element (d) in the net benefit calculation. For covering the costs, different types of investments were included, such as monetary gifts and grants that enabled UCM to pay for their running costs (staff salaries, etc.), but also investments that enabled UCM to avoid paying for costs, such as receiving a leasing car free of charge (Fig. 3). The economic loss associated with food waste that was not treated by anaerobic digestion but donated was also included. However, the cost of donated surplus food was omitted because the food had become unsellable, i.e. food waste from the retail perspective. The net economic benefit was calculated as a + b + d − c. For more details on each element, see Table E.1 in Appendix E.

3.2.2. Efficiency

The efficiency of the food donation scenarios was evaluated by setting the costs against their economic benefits, amount of food waste prevented, ecological savings, and social benefits (Goossens et al., 2019). For assessment of economic efficiency, the benefit-cost ratio was calculated by dividing the benefits by the costs (Investopedia, 2020). The food waste prevention and ecological efficiencies were calculated as the cost for reducing 1 ton of food waste and for abating 1 ton of carbon emissions (CO_2 eq.), through the ratio of cost to food waste reduction potential or emission savings, respectively (Goossens et al., 2019). Social efficiency was calculated as the cost of donating one food bag or meal, by dividing the costs by the number of food bags or meals donated.

3.3. Social impact assessment

To assess the social impacts of food donation, social life cycle assessment (S-LCA) methodology was applied for the goal, scope, and stakeholder definitions (UNEP, 2020). The goal of the assessment was to examine the *actual* social impacts of food donation for the key stakeholder categories, based on primary data. The scope was redistribution by UCM of surplus food from the retail gate to the recipients, including product end-use. The stakeholder categories chosen were consumers, workers, and the local community, based on the operating model of UCM. Based on categories, the key stakeholders were identified as recipients, employees, job trainees, volunteers, and the local community (Table 1).

3.3.1. Impact categories and impact subcategories

While inspiration was drawn from the S-LCA handbook issued by UNEP (2020), decisions on impact categories and subcategories assessed were largely based on their deemed relevance concerning the actual social and socio-economic impacts of the system studied, although data availability also played a role. An overview of the chosen stakeholder categories, stakeholders, impact categories, impact subcategories, and their corresponding indicators is presented in Table 1. The primary data used as indicators were collected from the

Table 1
An overview of the chosen stakeholder categories, stakeholders, impact categories, impact subcategories and their corresponding indicators used in the social impact assessment of food donation scenarios.

Stakeholder categories	Stakeholders	Impact categories	Impact subcategories	Indicators
Consumers	Recipients	Health and safety	Food security	High or marginal (0–1); Low (2–4); Very low (5–6)
			Individual dietary diversity	WDD score; min: 0; max: 9
			Nutrient rich foods score (food bags)	NRF11.3
		Equal opportunities	Gender ratio	Male/female (%)
		Economic security	Accrued savings due to receiving donated food	SEK/food bag or visit to soup kitchen
		Customer satisfaction	Service satisfaction	% happy (4 or 5) (scale 1–5)
			Increased life quality	% positive (4 or 5) (scale 1–5)
			Influence on health	% improved (4 or 5) (scale 1–5)
			Influence on personal economy	% improved (4 or 5) (scale 1–5)
Workers	Employees	Working conditions	Working time (full-time)	Working hours/week
	Job trainees		Working time (part-time)	Working hours/week
	Volunteers		Overtime	Hours/week
			Overtime payment	Yes/no
			Job positions	Full-time positions
			Fair salary	SEK/month
			Rehabilitation effectiveness	Job trainees entering labor market (%)
		Health and safety	Sickness absence	Long-term absences; >90 days
			Employee turnover	Turnover rate (%)
			Workplace violence; external threats	Number of incidents
		Equal opportunities	Gender ratio in work positions	Female workforce (%)
			Gender ratio in work positions	Female managers (%)
			Gender ratio in salary	Ratio of basic salary of men to women
Local community	Local community	Social responsibility	Surplus food redistributed	t/year
			Food bags or meals donated	No/year
			Poverty alleviation	Food bag recipients or soup kitchen visits/year
		Environment	Food waste prevented	t/year

stakeholders through a food security questionnaire (Appendix F), a dietary diversity interview (Appendix G), UCM staff interviews, UCM annual reports, and previous scientific studies, and by conducting nutritional calculations on the edible content of the food bags.

3.3.2. Food security questionnaire

Study participants were recruited by UCM staff during August 2020–April 2021 as previously described by Sundin et al. (2022). Data were collected from: 1) existing food bag recipients; 2) new food bag recipients; and 3) soup kitchen visitors. During the previous 30 days, the existing recipients had to be food bag recipients, while new recipients were not allowed to have received any of them. The questionnaire was available in Swedish, Arabic, and English. The following participants were recruited: 67 existing food bag recipients; 42 new food bag recipients; and nine soup kitchen visitors. For the demographics of the study participants, see Table H.1 in Appendix H. The participants were informed verbally and in writing about the study and informed consent was obtained from all participants, signed by them. No sensitive personal data was collected.

To investigate the food security status of the recipients, a self-administered six-item food security questionnaire was used (USDA, 2012) (see Appendix F). The mean scores for new and existing food bag recipients were compared, to evaluate whether food bags could potentially contribute to improved food security status among the recipients.

3.3.3. Dietary diversity questionnaire

The dietary diversity of the recipients was investigated by a 24-h dietary recall survey using the FAO dietary diversity questionnaire (Kennedy et al., 2013) (see Appendix G8). To conduct the questionnaire, 55 existing and 36 new food bag recipients were interviewed by nutritionists over the telephone. In addition, the staff of the soup kitchen conducted nine face-to-face interviews among their visitors. The participants recalled their food and drink intakes from the previous day during the interviews. The type of food and drink, their amounts, and the ingredients of composite meals were noted down. Based on the recalled dietary data, nine food groups were recorded as either consumed or non-consumed, to calculate an individual dietary diversity score (WDDS) (Kennedy et al., 2013). The mean dietary diversity scores of new and existing food bag recipients were compared to evaluate whether food bags improved the individual dietary diversity of the recipients.

3.3.4. Nutritional assessment of food bags

To assess the nutritional quality of the food bags, nutritional calculations were conducted based on the composition data obtained for the edible content of the 30 sampled food bags, using Nutrition Data (2022) software. The edible fractions of fruit and vegetables were calculated using literature values (De Laurentiis et al., 2018). The energy, nutrient, and dietary fiber contents of the food bags were expressed as mean values. To assess the number of days on which the food bags met daily reference intake values (DRI), the mean energy and macronutrient values were divided by the DRI values for women and men aged 31–60 years with an average physical activity level according to the Nordic nutrition reference values (NNR (2012)) (Nordic Council of Ministers, 2014). The macronutrient contents were also expressed as energy percent (E%) values and compared against the NNR (2012) reference E% values. Lastly, micronutrients were expressed as standardized for energy, i.e. nutrient density (per MJ). The nutrient densities of dietary fiber and all vitamins and minerals were calculated by dividing the mean nutrient values by the mean energy content of food bags (43.4 MJ). The nutrient densities were compared against NNR (2012) reference values for recommended nutrient density (per MJ) used for diet planning purposes for groups aged 6–65 years with a heterogeneous sex and age distribution.

3.3.5. Nutrient-rich foods index

To assess the nutritional quality of the food bags using a single indicator, the *nutrient-rich food* (NRF) index, more specifically the Sweden-tailored NRF11.3 index, was used (Bianchi et al., 2020). The NRF index assigns a *nutrient density* score based both on nutrients to be encouraged (qualitative nutrients, x in Eq. (3)) and nutrients to be limited (disqualitative nutrients, y in Eq. (3)) (Fulgoni et al., 2009). Eleven qualitative nutrients (protein, fiber, calcium, iron, folate, magnesium, potassium, and vitamins A, C, D and E) and three disqualitative nutrients (saturated fat, sodium, and total sugar) were considered in this study.

Since the food bags were donated weekly, the mean nutrient values of the food bags were first divided by seven (days) and then calculated as percentage of daily values. The Codex Alimentarius reference values (Lewis, 2019) were used as DRIs and maximum recommended intakes (MRIs) for all nutrients except dietary fiber, for which the NNR (2012) reference value was used. The percentages of daily values of qualitative nutrients were capped at 100 % where applicable, to avoid overstating their impact. The NRF11.3 score was calculated as:

$$\boldsymbol{NRFx.y} = \left(\sum \mathbf{1}-\boldsymbol{x}\left(\frac{\boldsymbol{Qualitative\ nutrient}}{\boldsymbol{DRI}}\right)\right) - \left(\sum \mathbf{1}-\boldsymbol{y}\left(\frac{\boldsymbol{Disqualitative\ nutrient}}{\boldsymbol{MRI}}\right)\right) \tag{3}$$

4. Results

The results showed that food donation to reduce food waste was of benefit to the environment and also brought added economic and social values, for the recipients in particular. Despite substantial rebound effects offsetting some of the potential environmental impact savings, the overall environmental performance of food donation was superior to that of anaerobic digestion. It is important to note, however, that the environmental trade-offs caused by the rebound effects gave other significant benefits, e.g. the accrued savings relieved the personal finances of the recipients and allowed purchases of necessities such as clothing and healthcare. While contributions from several stakeholders were necessary to fund the food donation scenarios, positive economic value was generated in the food bag scenario and was mainly transferred to the recipients. The results suggested that food bags also had potential to alleviate the food insecurity of the recipients, although they did not fully solve the issue. Further, due to their high nutrient density, food bags had the potential to improve nutrition intake by the recipients.

4.1. Environmental impacts

With respect to environmental impact, the results indicated that the food bag scenario generated the lowest impact for 17 out of 18 midpoint indicators, including global warming, acidification, and land use. For these 17 categories, the values obtained were negative, indicating mitigation of the environmental impacts (Table 2). The anaerobic digestion scenario generated the highest environmental impacts in 11 out of 18 midpoint impact categories. However, the impacts were still negative in 10 of the categories, indicating impact mitigation. The soup kitchen scenario had the highest environmental impacts in seven categories, while 11 categories had negative values indicating impact mitigation.

When the midpoint indicators were aggregated to endpoint level impacts, the food bag center continued to perform best in the ecosystem damage and human health impact categories, while anaerobic digestion had the highest impacts in both these categories (Table 2). The ecosystem damage results were largely due to the GWP, land use, and terrestrial acidification midpoint results, whereas GWP and fine particulate matter results contributed the most to the human health results across all scenarios (see Figs. I.1 and I.2 in Appendix I). In both categories, the food bag scenario resulted in the lowest environmental impacts and the anaerobic digestion scenario resulted in the highest.

Overall, the substitution effect was the largest contributor to the net results obtained, while food waste management operations, such as transport, played a minor role (Fig. 4 presents an example for GWP). Some of the potential emission savings, largely due to the substitution

Table 2
Environmental impacts per 1 kg food waste at retail gate comparing three different food waste management scenarios, anaerobic digestion, redistribution via food bag center and redistribution via soup kitchen. Both the midpoint and endpoint levels are presented. The best environmental outcome for each impact category is indicated by light green and for the worst by light pink.

Environmental impact method	Impact category	Units	Anaerobic digestion scenario	Food bag scenario	Soup kitchen scenario
Midpoint level	Global warming	kg CO_2 eq	-2.3×10^{-1}	-7.7×10^{-1}	-2.6×10^{-1}
	Stratospheric ozone depletion	kg CFC11 eq	-4.7×10^{-8}	-6.8×10^{-6}	-3.5×10^{-6}
	Ionizing radiation	kBq Co-60 eq	2.1×10^{-2}	-6.7×10^{-3}	4.5×10^{-2}
	Ozone formation. Human health	kg NOx eq	-1.3×10^{-4}	-1.6×10^{-3}	-2.0×10^{-4}
	Fine particulate matter formation	kg PM2.5 eq	-5.9×10^{-5}	-1.3×10^{-3}	-3.4×10^{-4}
	Ozone formation. Terrestrial ecosystems	kg NOx eq	-1.4×10^{-4}	-1.7×10^{-3}	-2.0×10^{-4}
	Terrestrial acidification	kg SO_2 eq	-2.0×10^{-4}	-7.8×10^{-3}	-3.6×10^{-3}
	Freshwater eutrophication	kg P eq	-4.2×10^{-7}	-1.8×10^{-3}	-3.7×10^{-4}
	Marine eutrophication	kg N eq	3.9×10^{-6}	-2.2×10^{-3}	-1.5×10^{-3}
	Terrestrial ecotoxicity	kg 1.4-DCB	1.3 × 10−1	−1.3	3.2 × 10−1
	Freshwater ecotoxicity	kg 1.4-DCB	4.6×10^{-5}	-1.0×10^{-2}	9.1×10^{-3}
	Marine ecotoxicity	kg 1.4-DCB	9.5×10^{-5}	2.1×10^{-3}	1.6×10^{-2}
	Human carcinogenic toxicity	kg 1.4-DCB	-1.8×10^{-4}	-1.1×10^{-2}	9.6×10^{-3}
	Human non-carcinogenic toxicity	kg 1.4-DCB	3.8×10^{-3}	−1.3	−2.6 × 10−1
	Land use	m^2a crop eq	8.4×10^{-3}	−1.8	−5.5 × 10−1
	Mineral resource scarcity	kg Cu eq	-2.3×10^{-4}	-3.4×10^{-4}	2.3×10^{-3}
	Fossil resource scarcity	kg oil eq	-8.7×10^{-2}	-9.5×10^{-2}	1.0×10^{-2}
	Water consumption	m^3	6.9×10^{-4}	-5.8×10^{-2}	-7.7×10^{-3}
Endpoint level	Ecosystem damage	species.years	$-6.2 \times 10{-}1^{0}$	-2.1×10^{-8}	-6.7×10^{-9}
	Human health	DALYs	-2.5×10^{-7}	-1.9×10^{-6}	-4.9×10^{-7}

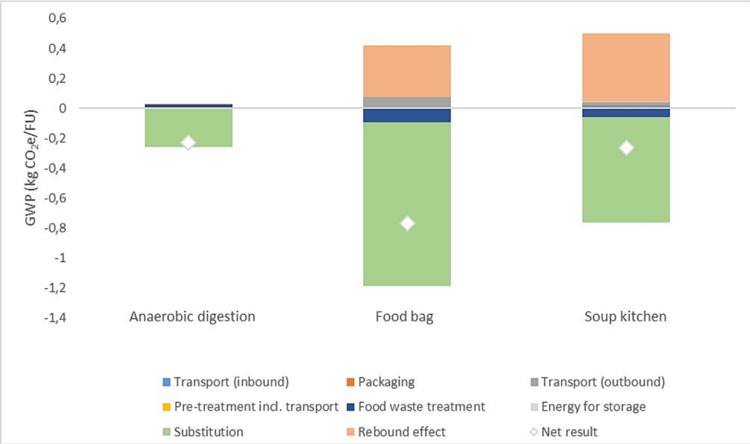

Fig. 4. Net global warming potential (GWP) impact, broken down into contributing food waste management operations, substitution effect, and rebound effect for the three scenarios (anaerobic digestion, redistribution via food bag center, and redistribution via soup kitchen).

effect, were offset by the rebound effect. With respect to GWP, the rebound effect was 31 % (food bags), 64 % (soup kitchen), and 2 % (anaerobic digestion).

4.1.1. Sensitivity analysis

In sensitivity analysis, several parameters were altered to test their impact on GWP. Changes tested included different allocation for Agri-footprint datasets, alternative substitution products, and substitution rates, along with adjustments in prices and savings (Fig. 5). Switching the mass allocation method to economic allocation did not change the results for anaerobic digestion, but changed the result for the food bag and soup kitchen scenarios by 18 % and 86 %, respectively. However, the overall order of the scenarios was not affected. Similarly, the substitution of diesel instead of natural gas did not affect the overall results markedly with a 20 % change for anaerobic digestion, although anaerobic digestion results became slightly more climate negative than the results for soup kitchen. The rebound effects of food donation scenarios were not sensitive to price changes (±15 %). However, the rebound effects showed high sensitivity to amount of accrued savings (±SD = ±131 SEK for food bags; ±36 SEK for soup kitchen), and the proportion of savings spent on food (0 %; 100 %), both of which led to backfire effects in the soup kitchen scenario. The substitution effects were sensitive to changes in the amount of food substituted (50 %; 70 %). The sensitivity of the above mentioned parameters were also tested on land use with similar results as for GWP as shown in Fig. J.1 in Appendix J.

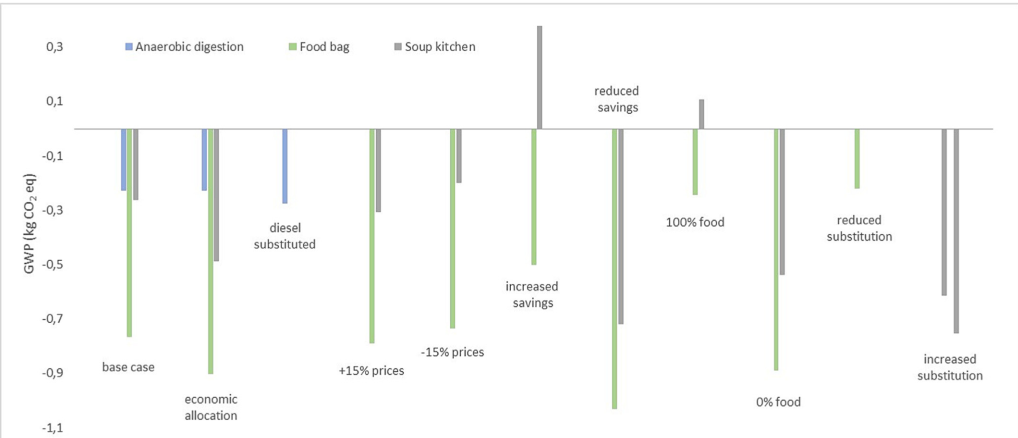

Fig. 5. Global warming potential (GWP) results in sensitivity analyses in comparison with the base case for the three scenarios (anaerobic digestion, redistribution via food bag center, and redistribution via soup kitchen), expressed per kg donated food. The results were sensitive to changes in accrued savings, proportion of savings spent on food, and proportion of food substituted.

4.2. The economic value of surplus food donation

4.2.1. Net economic benefits

The net economic result for the food bag scenario was positive (1502 kSEK) indicating that positive economic value was generated (Table 3). In contrast, the net result for the soup kitchen was negative (−622 kSEK) indicating that the costs of this redistribution activity exceeded the benefits generated. Overall, the net benefit calculations highlighted the high level of investment required from different stakeholders to run the redistribution activities.

4.2.2. Efficiency

The benefit-cost ratio of the food bag center was 1.37 and that of the soup kitchen was 0.75, where a value >1.0 indicates a positive net value outcome (Table 4). As regards economic efficiency in food waste prevention, the cost of preventing 1 ton of food waste was 28 kSEK for the food bag center, but more than twice as much (64 kSEK) for the soup kitchen. As regards ecological efficiency, the cost of 1 ton CO_2e abated was 27 kSEK for the food bag center and eight-fold higher (216 kSEK) for the soup kitchen. As regards social efficiency, the cost of donating one food bag was 292 SEK for the food bag center and the cost of donating one meal was 25 SEK for the soup kitchen.

4.3. The social value of surplus food donation

Three key stakeholder groups, i.e. consumers (recipients), workers (employees, job trainees, volunteers) and the local community were included in the social assessment of surplus food donation. An overview of the results with the chosen indicators per stakeholder and scenario is presented in Table 5. Below, the most important results are described separately for the recipient and worker stakeholder groups.

4.3.1. Recipients

When assessing the social values generated through surplus food redistribution for the *recipients* stakeholder group, the main values considered related to nutritional aspects such as food security and dietary diversity status of the recipients, as well as the nutritional value of the food bags. The results revealed that the mean food security score of the new food bag recipients was 3.3, whereas the score of the existing food bag recipients was 2.4. Although the score of the existing recipients indicated better food security in comparison with new recipients, their food security status was still low. For the soup kitchen visitors, the food security status (score 4.3) was lower than for both categories of food bag recipients.

Overall, there was no difference in the dietary diversity of the recipients (5.5 for new food bag recipients; 5.3 for existing food bag recipients), although higher intake frequencies in some food groups frequently provided by the food bags, such as white roots and tubers (+70 %), vitamin A-rich tubers (+10 %) and green leafy vegetables (+18 %), were observed for existing recipients. However, consumption frequency of legumes, nuts, and seeds (−51 %), eggs (−15 %), and sweets (−15 %) was lower for existing recipients than for new recipients. The dietary diversity score of the soup kitchen visitors was 3.4, which was considerably lower than the score of the existing food bag recipients (5.3).

The nutrient quality data for the food bags indicated overall good quality. The bags contained macronutrients such as protein, carbohydrates, and fat, in proportions that were largely within the reference values (Table 6). In addition, the bags were low in sugar and the fat they contained was of good quality. The bags were also nutrient-dense and in line with reference values for most vitamins and minerals, with a high content of vitamins A, C, and E and niacin (Table 7). Further, the bags were high in dietary fiber, and the salt content was below the maximum reference value. Consequently, the nutrient-rich foods score (NRF11.3) of the food bags was 729, indicating high nutrient density (min −300; max 1100). The energy content of the food bags covered the energy needs of an adult person aged 31–60 years, with an average level of physical activity, for approximately four days.

4.3.2. Workers (employees, job trainees, and volunteers)

To assess the social values generated through surplus food redistribution for the *workers* stakeholder (*employees, job trainees, volunteers*), the main values investigated were related to their working conditions, health and safety, and equal opportunities. The employees had normal working hours, and fair salaries (above minimum wage), and there had been no long-term sick leaves (Table 5). The turnover rate of employees was low (0), but that for food bag center volunteers was higher (8). Approximately half of the job trainees received employment following their training period. The female managers at both units indicated equal opportunities.

5. Discussion

This study investigated all three aspects of sustainability in relation to surplus food donation in order to gain a holistic view. The results

Table 3
A cost-benefit analysis of Uppsala City Mission food bag center and soup kitchen for 2020.

Stakeholders	Benefit/cost variable	Food bag scenario kSEK/year	Soup kitchen scenario kSEK/year
	Benefits[a]		
Recipients	Accrued savings due to receiving donated food	2587 (47 %)	304 (16 %)
Retailers	Avoided food waste treatment	34 (1 %)	8 (1 %)
Employees	Employment (salaries, benefits)	1956 (35 %)	1326 (69 %)
Job trainees	Employment due to job training	947 (17 %)	271 (14 %)
	Total	5524 (100 %)	1909 (100 %)
	Costs[b]		
Property owners	Premises	180	180
Car leaser	Vehicle	60	25
Private and public donors	Gifts, grants, raised funds	2811	1872
Municipality	Compensation paid for job trainees	656	241
Food waste treatment plant	Loss of food waste[c]	*0*	*0*
Volunteers	Volunteer hours	226	213
Recipients	Membership fees	89	0
	Total	4022	2531
	Net benefits [benefits-costs]	1502	−622

[a] Values of outcomes created through food redistribution activities.
[b] Funding covering for the cost linked to redistribution process.
[c] Due to being a tax-funded company aiming at zero financial result, where deficits and surpluses are settled against subscriber fees, and due to the amount of lost food waste corresponding to <0.5 % of the total volume of food waste treated, the value was considered negligible.

Table 4
Efficiency indicators of Uppsala City Mission food bag center and soup kitchen for 2020.

Efficiency dimension	Indicator	Food bag scenario	Soup kitchen scenario
Economic benefits	Benefit-cost ratio	1.37	0.75
Food waste prevention	Cost of 1 ton food waste prevented[a] (kSEK)	28	64
Ecological savings	Cost of 1 ton CO_2e abated (kSEK)	27	216
Social benefits	Cost of donating one food bag or meal[b] (SEK)	292	25

[a] Effectiveness (amount of redistributed food eaten) derived from Sundin et al. (2022).
[b] Corresponds to food bags donated by the food bag center or meals (400 g/portion) donated by the soup kitchen.

showed that food donation was a way to reduce food waste providing benefits for the environment while adding social value but requiring economic investments from several stakeholders. Food bag donation generated the largest environmental impact savings in all but one of the 18 midpoint categories considered in comparison with anaerobic digestion, but also in both endpoint categories, *ecosystem damage,* and *human health*, a novel contribution of the study. However, considerable rebound effects (31 % for food bags; 64 % for soup kitchen) were found to offset some of the potential GHGE savings but despite them, the overall results were still aligned with the waste hierarchy and with previous findings in studies where rebound effects were not considered (Eriksson and Spångberg, 2017; Moult et al., 2018). Further, the midpoint-level results showed that redistribution offers higher overall environmental savings in comparison with anaerobic digestion of food waste, also suggested by some previous studies (Albizzati et al., 2019; Brancoli et al., 2020; Damiani et al., 2021).

The net environmental gains generated by the two food donation scenarios were greatly influenced by the substitution and rebound effects (Fig. 4), rather than the actual process-related impacts. Meanwhile, sensitivity analyses revealed high sensitivity of the net environmental results to the amount of food substituted, but also to the amount of savings accrued and the degree to which these savings were spent on food (Fig. 5), thus, these results are best interpreted on their magnitude level. Nevertheless, the aforementioned factors also explained some of the differences in net environmental outcome between the two donation scenarios, due to the units serving different socio-economic recipient groups. Food bags were substituted to a higher degree than soup kitchen meals, but food bag recipients spent their savings proportionally less on food, leading to a lower environmental impact and thus lower rebound effect. This difference between the recipient groups was also reflected in the better food security and dietary diversity status of food bag recipients compared with soup kitchen visitors.

Table 5
An overview of the actual social impacts of the food bag center and soup kitchen of Uppsala City Mission based on 2020 data. The food security and dietary diversity scores of food bag recipients concerned those participants who had received food donation during a minimum of 30 previous days.

Impact categories	Impact subcategories	Indicators	Food bag scenario	Soup kitchen scenario
			Recipients	Recipients
Health and safety	Food security	High or marginal (0–1); Low (2–4); Very low (5–6)	2.4	4.3
	Individual dietary diversity	WDD score; min: 0; max: 9	5.3	3.4
	Nutrient-rich foods score (food bags)	NRF11.3	729	
Equal opportunities	Gender ratio	Male/female (%)	47/53	75/25
Economic security	Accrued savings due to receiving donated food	SEK/food bag or visit to soup kitchen	165	25
Customer satisfaction[a]	Service satisfaction	% happy (4 or 5) (scale 1–5)	87	
	Increased life quality	% positive (4 or 5) (scale 1–5)	74	
	Influence on health	% improved (4 or 5) (scale 1–5)	51	
	Influence on personal finances	% improved (4 or 5) (scale 1–5)8	84	

Impact categories	Impact subcategories	Indicators	Food bag scenario			Soup kitchen scenario		
			Employees	Job trainees	Volunteers	Employees	Job trainees	Volunteers
Working conditions	Working time (full-time)	Working hours/week	40			40		
	Working time (part-time)	Working hours/week	30			30		
	Overtime	Hours/week	0			0		
	Overtime payment	Yes/no	Yes			Yes		
	Job positions	Full-time positions	4.25	7	15	1.75	1	24
	Fair salary	SEK/month	29,000	Compensation	0	27,000	Compensation	0
	Rehabilitation effectiveness	Job trainees entering labor market (%)		50			100	
Health and safety	Sickness absence	Long-term absences >90 days	0	0	0	0	0	0
	Employee turnover	Turnover rate (%)	0	50	8	0	100	0
	Workplace violence; external threats	Number of incidents	0	0	0	0	0	0
Equal opportunities	Gender ratio in work positions	Female workforce (%)	70			50		
	Gender ratio in work positions	Female managers (%)	100			100		
	Gender ratio in salary	Ratio of basic salary of men to women	1			1		

Impact categories	Impact subcategories	Indicators	Food bag scenario	Soup kitchen scenario
			Local community	Local community
Social responsibility	Surplus food redistributed	t/year	193	45
	Food bags or meals donated	#/year	13,756	9543
	Poverty alleviation	Food bag recipients or visits/year	250	12,175
Environment	Food waste prevented	t/year	144	40

[a] Results based on Topor (2021).

Table 6
Energy and macronutrient content of weekly food bags in comparison to reference values.

Energy and macronutrients		Mean	Reference value[a]	Days meeting RDI[b]	E%[c]	Reference value E%[d]
Energy	kJ	43,439	8800/11000	4.9/3.9		
Protein	g	310	70/82	4.4/3.8	12	10–20
Carbohydrates	g	1535	271/340	5.7/4.5	60	45–60
Sucrose	g	185			7	<10
Total fat	g	292	77/97	3.8/3	24[e]	25–40
SFA	g	103			9	<10
MUFA	g	113			10	10–20
PUFA	g	47			4[e]	5–10

[a] Reference daily intake (RDI) values for energy of women/men of 31–60 years of age corresponding to an average physical activity level, which have been used as a basis for the reference values of protein, carbohydrates and total fats (NNR, 2012).
[b] Number of days the energy and macronutrient content of food bags meets the RDI of women/men.
[c] Percentage of macronutrient of the total energy content of food bags.
[d] Reference values according to NNR (2012). For sucrose, the reference value refers to added sugars, but the presented mean and E% include both added sugars and natural sources of sucrose.
[e] Value not meeting the reference value.

Private and public investments were required to run the food donation units, but positive economic value was generated only in the case of the food bag scenario. In contrast, previous assessments resulted in considerably higher economic value due to differences in assumptions and scope (Cicatiello et al., 2016; SVA, 2013), underscoring the importance of interpreting such results within their context. Cicatiello et al. (2016) allocated donated food full retail value, but excluded the costs of volunteer labor and salaries from the scope of their assessment, resulting in a benefit-cost ratio of 4.6. Another study counted volunteer time as an investment, but excluded the value of food, as it was considered waste, giving a benefit-cost ratio of 2.75 (SVA, 2013). In contrast to both previous assessments, the present study included accrued savings and salaries in the benefit-cost calculation, resulting in a ratio of 1.37 for the food bag scenario but only 0.75 for the soup kitchen scenario, due to a lower amount of accrued savings. This was also the main factor contributing to the negative net benefit result for the soup kitchen (−622), as the lower benefits generated did not cover the relatively high labor costs in that scenario.

Table 7
Vitamin, mineral and fiber content of food bags in comparison to reference values.

Vitamins, minerals and fiber		Mean	Reference value[a]	Number of days meeting reference value[b]	Nutrient density per MJ	Reference value[c]
Vitamin A (RE)	RE	5205	800	6.5	120	80
Vitamin D	μg	19	10	1.9	0.4[d]	1.4
Vitamin E	α-TE	69	9	**7.7**	1.6	0.9
Vitamin B1 (Thiamin)	mg	9	1.2	**7.5**	0.2	0.12
Vitamin B2 (Riboflavin)	mg	8	1.2	6.3	0.17	0.14
Niacin	NE	170	15	11.3	3.9	1.6
Vitamin C	mg	1394	100	13.9	32.1	8
Vitamin B6 Pyridoxine	mg	11	1.3	8.8	0.3	0.13
Vitamin B12	μg	9	2.4	3.9	0.2	0.2
Folate	μg	2467	400	6.2	56.8	45
Phosphorus	mg	6703	700	9.6	154.3	80
Iron	mg	53	14	3.8	1.2[d]	1.6
Calcium	mg	3954	1000	4.0	91.0[d]	100
Potassium	g	24	3.5	6.9	0.6	0.35
Magnesium	mg	2347	310	7.6	54.0	32
Sodium	mg	9110	2000	4.6	209.7	245
Selenium	μg	139	60	2.3	3.2[d]	5.7
Iodine	μg	478	150	3.2	11.0[d]	17
Zinc	mg	47	11	4.2	1.1[d]	1.2
Dietary fiber	g	190	25–35	7.6	4	3

[a] Codex Alimentarius nutrient reference values for vitamins and minerals (where nutrient reference values are based on the daily intake value that is estimated to meet the nutrient requirement of 98 % of an apparently healthy individual, thus the RDI or RDA) for the general population, identified as individuals older than 36 months (FAO and WHO, 2019). Sodium not to be exceeded. Fiber according to NNR (2012).
[b] Number of days the nutrient content of one food bag meets the reference value of nutrient.
[c] NNR (2012) reference values for recommended nutrient density (per MJ) used for diet planning purposes for groups of 6–65 years of age with a heterogeneous sex and age distribution. Sodium not to be exceeded.
[d] Value not meeting the reference value.

The economic value received by the recipients generated social value by improving their personal finances, playing potentially an important role as a factor for increased choice among recipients (Wolfson and Greeno, 2020). Furthermore, our results showed that the donated food was well-balanced and nutrient-dense, due to a large proportion of perishable foods, such as fruit, vegetables, and dairy products similar to the findings by Mousa and Freeland-Graves (2019a) and Vittuari et al. (2017). Some studies, however, identified a nutrient imbalance in food donations but concluded that larger proportions of perishable foods would resolve that issue (Brennan and Browne, 2021; Simmet et al., 2017; Tse and Tarasuk, 2008). Moreover, previous studies have identified a positive effect of food donations rich in perishable foods on recipients' diets (Mousa and Freeland-Graves, 2019b; Nogueira et al., 2021b, 2021a). Thus, high nutrient density of surplus food provides potential to contribute positively to recipients' diets, further supported by the previous finding of high recipient acceptance of the donated food (Sundin et al., 2022).

The food donations also showed potential for alleviating recipients' food insecurity, as found in previous studies (Mousa and Freeland-Graves, 2019b; Wolfson and Greeno, 2020), although the recipients were not food-secure according to the survey results. The average energy content of the food bags met the energy requirements of an average adult for four days. Considering that, on average, the recipients were families of four (two adults and two children) receiving one food bag/week, it is reasonable that the donations only had a relieving effect, especially since the parents could be expected to prioritize their children's food intakes. The school meal scheme provided to all children free of charge in Sweden aims to cover one-third of children's nutritional requirements (Osowski et al., 2015), and food donations can be an important supplement to provision by the welfare state.

A strength of the present study lay in including all three aspects of sustainability, to gain an understanding of trade-offs between these and also a more comprehensive view of food donation. In addition to discovering that the rebound effects contributed to other important values, such as economic and social benefits for the recipients, the results showed that the soup kitchen did not generate as high environmental gains or positive economic value as food bags did. However, the economic assessment did not capture the value of donated food that did not substitute for any food, which still likely played an important role in helping the most vulnerable in society. It should also be acknowledged that the soup kitchen contributed to the effectiveness of the food bag center, annually salvaging 16 tons of its surplus food with a very short shelf-life (Sundin et al., 2022), suggesting that a *hybrid model* of redistribution combining *direct* and *indirect donations* could be a key success factor. Further studies are, however, needed to understand the interdynamics of such models and how to optimize these.

Another strength of the present study was the use of primary input data in the assessments, due to access to UCM data. However, using the ReCiPe method, representing European conditions, might not have been able to fully capture the local conditions in the LCA. While no randomized method was used for recruiting study participants, a strength of the study was to recruit recipients instead of relying on charity personnel's perceptions on issues concerning recipients, a method commonly applied in previous studies (Mirosa et al., 2016; Vittuari et al., 2017). However, the low participant rate at the soup kitchen (due to the Covid-19 pandemic) was a weakness and challenging to overcome, whereas telephone interviews were used to overcome this issue with the food bag recipients. Further, it should be noted that the economic and social assessments were not exhaustive and other valuable factors could have been included, such as the monetary value of abating environmental impacts or feeling shame as a recipient. Limitations of the method itself should also be kept in mind when using the results for decision-making. For example, the assessment did not consider any initial investment costs and the results are therefore only generalizable to a donation scheme that is already operational, and not to establishment of new food donation organizations. However, the potential of surplus food donation can be generalized to other countries, as retail surplus food even outside Sweden often consists of perishable foods (bread, fruit, and vegetables) with high nutritional value (Schneider and Eriksson, 2020).

UCM's swift food handling process has previously been identified as a key to its success (Sundin et al., 2022) and also a prerequisite for realizing environmental gains of food donation (Damiani et al., 2021). High recipient acceptance of redistributed food is another key factor, as food acceptance can be complex (Leng et al., 2017; Sundin et al., 2023). In fact, most of the values would not have been generated if the donated food had been discarded instead of eaten by recipients, regardless of the efficiency of the redistribution process. To maximize the benefits of food donations, policymakers should seek to enable charities to meet the dietary needs and preferences of recipients to the highest degree possible. The more surplus food eaten, the higher the substitution effect leading to accrued savings, while the lower the need to spend accrued savings on complementary foods, the lower the rebound effect. In a way, UCM is already addressing this by adapting food bags to the dietary preferences of recipients (e.g. lactose-free and vegetarian) (Sundin et al., 2022). Another option could be to adjust the contents of food bags according to the recipient's family size, in order to distribute the food in a potentially fairer way.

The results showed multiple environmental benefits of food donation as a food waste management option compared with anaerobic digestion. Food donation also imparted social values to vulnerable groups while food and nutrients were salvaged for their intended purpose, i.e. human consumption. However, while retailers are showing increasing interest in surplus food redistribution, at present only a fraction is donated (Huang et al., 2021; Johansson, 2021). Lack of financial incentive has been identified as a major barrier to surplus food donation (Deloitte et al., 2020). This could be due to retailers' decision-making being steered mainly by economic considerations, while environmental and social factors play a minor role (Rosenlund et al., 2020). Under recent Swedish legislation, retailers are exempted from paying VAT on their food donations (Swedish Food Agency, 2022). However, as this study showed, the economic value transferred to retailers due to surplus food redistribution is negligible (1 % of total benefits). To provide economic gains to retailers, an appropriate fiscal framework making surplus food redistribution more cost-effective for retailers than disposal must be implemented. A waste tax deduction could be one option, as it could activate food redistribution while generating multi-stakeholder benefits (Franco and Cicatiello, 2021). Alternatively, legislation must be used to enforce the use of higher-priority waste handling options to save natural resources, as suggested by Eriksson et al. (2023). These measures could be used in parallel, as edible food waste could be redistributed and inedible food waste sent to anaerobic digestion when prevention is not achievable (Johansson, 2021).

6. Conclusions

This study showed that surplus food donation was a way to reduce food waste benefitting the environment, with added economic and social value to vulnerable groups, in particular, in Sweden. While there were some trade-offs, such as rebound effects, these were outweighed by the benefits generated. However, the system for handling surplus food donations required economic investments from various stakeholders, as well as surplus food free of charge from retailers. Food donation can be seen as a transfer system, where economic values and retailers' food waste are transferred and converted by food centers into environmental, economic, and social benefits. However, there is no incentive for retailers to donate their surpluses resulting in a lack of *win-win*. To realize the potential of surplus food donation, policy measures should be better aligned with the waste hierarchy so as to stimulate prevention and reuse for human consumption. Although surplus food donations organized by charities cannot be considered a long-term solution, due to their inability to solve the root causes of food insecurity and food wastage, their activities can alleviate both these issues simultaneously and therefore have short-term potential to contribute to a more sustainable society.

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CRediT authorship contribution statement

Niina Sundin: Conceptualization, Methodology, Investigation, Data curation, Software, Validation, Formal analysis, Visualization, Writing – Original draft. **Louise Bartek:** Methodology, Data curation, Software, Validation, Writing – review & editing. **Christine Persson Osowski:** Conceptualization, Methodology, Formal analysis, Writing – Review & Editing. **Ingrid Strid:** Conceptualization, Methodology, Writing – Review & Editing. **Mattias Eriksson:** Conceptualization, Methodology, Formal analysis, Writing – Review & Editing, Funding acquisition.

Declaration of competing interest

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

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Appendix A. Supplementary data

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Full length article

Investigating goal conflicts in menu planning in Swedish school catering on the pathway to sustainable development

Niina Sundin [a,*], Christopher Malefors [a], Maja Danielsson [a], Marina Hardiyanti [a], Christine Persson Osowski [b], Mattias Eriksson [a]

[a] Department of Energy and Technology, Swedish University of Agricultural Sciences, Box 7032, Uppsala SE-75007, Sweden
[b] Department of Public Health Sciences, Mälardalen University, Sweden

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ABSTRACT

The 260 million publicly funded school meals served annually in Sweden generate 21.000 tons of food waste. At national level, school meals should meet the goal of food waste reduction, together with various other goals such as meeting nutritional requirements, being environmentally friendly and, most importantly, achieving high acceptance among schoolchildren. There is a preconception among kitchen staff that the most popular school meals drive food waste in Swedish school catering and that vegetarian dishes increase food waste, despite being less popular than meat options. By applying mixed methods, this study investigated possible goal conflicts between reduced food waste, high acceptance, and vegetarian options on the lunch menu. An overall aim was to gain knowledge on how lunch menus could be adapted for increased sustainability. Kitchen staff from 10 Swedish primary and secondary schools were interviewed to identify the most popular and unpopular meals, and food waste quantification data and lunch menus from 61 school canteens were analyzed. The results showed that, while the common perception of popular and vegetarian meals creating most waste was held by kitchen staff, it proved to be untrue. In fact, popular school meals and vegetarian options generated less waste than unpopular meals. A vegetarian paradox was detected in interviews, with vegetarian options considered unpopular but with several vegetarian options among the most popular dishes. Thus, school-catering units should stop serving unpopular meals and shift their focus to serving popular nutritious meals, including popular plant-based options, as part of efforts to make school meal schemes more sustainable.

1. Introduction

Food waste is a global issue that comes at an enormous environmental, social, and economic cost of 2.6 trillion USD per year (FAO, 2014). To tackle the food waste issue, the United Nations Agenda for Sustainable Development has set a global target to halve food waste per capita at retail and consumer level by 2030 (United Nations, 2015). To contribute to this global target, Sweden has implemented an action plan to reduce food loss and waste by 2030 (Swedish Food Agency et al., 2018). Large amounts of food are wasted in Sweden, as excess food intake (i.e., metabolic food waste), amounting to 0.5 million tons per year, and as direct waste, estimated at 1.1 million tons per year (Hultén et al., 2022; Sundin et al., 2021). In 2020, an estimated 33,000 tons of food waste were disposed by large-scale catering establishments in Sweden (Hultén et al., 2022). The actual amount of food waste varies between school kitchens and between different areas in Sweden, but in 2020 the national average for total food waste from school kitchens was approximately 50 gs per pupil, excluding beverages (Malefors et al., 2022a). Since food waste is generated throughout the entire food supply chain, reduction efforts are necessary at each step, including public catering establishments in schools and preschools, to reach the overall reduction target by 2030.

School meals in various forms are served around the world, but the Swedish school meal scheme is considered unique due to its inclusiveness. A midday meal is served free of charge every weekday to all pupils of compulsory school age (6–15 years) and to most students in upper secondary school, regardless of parental income (Swedish Parliament, 2010). Thus every year, 260 million publicly funded school meals are served in Sweden (Swedish Food Agency, 2022a). The overall responsibility for these meals lies with municipalities, and the practicalities of planning and cooking, and kitchen facilities, may differ across Sweden. However, in all cases the meals are served hot, usually with

* Corresponding author.
E-mail address: niina.sundin@slu.se (N. Sundin).

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several alternatives to choose from, and are accompanied by salad, bread, spread, and milk or water. Since 2011, Swedish law stipulates that school meals must be nutritious (Swedish Parliament, 2010), and according to national guidelines they must supply one-third of recommended daily energy and nutrient intake in children (Swedish Food Agency, 2021). The national guidelines state the importance of pupils enjoying school meals, while at the same time challenging their taste preferences. School meals are also intended to be a teaching occasion (educational meals), where children can learn healthy eating habits and are encouraged trying new foods (Persson Osowski and Fjellström, 2019). Exposing children to food may increase their liking of different foodstuffs (Birch and Fisher, 1996; Cooke, 2007), whereas forcing them to eat may result in food rejection (Batsell et al., 2002). Learning healthy eating habits is essential, for example, in preventing overweight and obesity in children, the prevalence of which is high and increasing with age in Sweden (Public Health Agency of Sweden, 2019). Thus, the school meal scheme serves an important function in promoting public health in Sweden contributing to a more equal society and sustainable development.

In addition to meeting nutritional requirements through school meals, there is an increasing focus on environmental sustainability, through reduced food waste and also by making conscious choices, such as cooking more plant-based meals to reduce the carbon footprint. Already, 70% of Swedish municipalities have set targets to reduce food waste, while more than 33% have taken their own initiative in setting reduction targets for the climate impact of food consumption (Swedish Food Agency, 2022b). Offering a daily vegetarian alternative is not mandatory in Swedish school catering but has become increasingly common, with 63% of municipalities offering vegetarian alternatives to their pupils in all primary and secondary schools, in accordance with the national guidelines (Swedish Food Agency, 2022b). However, in order for school meals to fulfill their fundamental purpose in terms of promoting public health while being environmentally sustainable, the meals must achieve high acceptance among schoolchildren. Food that is not eaten, no matter how nutritious or environmentally conscious, serves no purpose.

Meeting all these goals simultaneously could be challenging. In fact, there is a common perception among kitchen staff in Sweden that the most popular school meals generate the most food waste, suggesting a potential conflict between high acceptance and environmental sustainability of school meals (Eriksson et al., 2016; Prim and Broberg, 2013). Consequently, kitchen staff may limit the quantity of food that pupils can be served in a single serving, in order to reduce food waste. These types of actions are unpopular among pupils, who interpret them as an attempt to limit how much they are allowed to eat (Bjernevall, 2022).

It is not clear whether the common perception that popular school meals generate most waste is true, but it is treated as fact since catering staff use it as justification to reduce the portion size of popular dishes. It may have arisen from the notion of greater wastage of popular meals due to schoolchildren taking larger portion sizes of these meals. Larger portion sizes have been identified as a factor significantly increasing plate waste in school and work canteens (Boschini et al., 2020; Lorenz-Walther et al., 2019; Pires et al., 2022; Steen et al., 2018). When popular school meals are served, pupils prefer to opt for larger portions instead of awaiting second servings, to avoid unnecessary queuing time and due to a fear that the food will run out (Eriksson et al., 2016). Pupils also seem to think that they can eat more of their favorite dishes, although in reality they cannot always finish the whole portion (Eriksson et al., 2016; Modin, 2011). However, not liking the food is reported to be another main reason for pupils wasting served school meals (Boschini et al., 2020; Cordingley et al., 2011; Prim and Broberg, 2013). Unpopular school meals have also been associated with more serving waste with food being prepared, but not served (Cordingley et al., 2011).

To assess the wastage levels of the most popular and unpopular school meals, the preferences of schoolchildren need to be known. According to previous studies conducted in Sweden, the most popular meals include pancakes, hamburgers, tacos, pizza, chicken, pasta Bolognese, and lasagna (Eriksson et al., 2016; Prim and Broberg, 2013). The most unpopular meals are reported to be fish with potatoes, black pudding, potato pancakes, and beef with potatoes (Eriksson et al., 2016). However, evidence is lacking regarding the most popular and unpopular vegetarian school meals in Sweden and the degree to which these are wasted. Unpopularity of vegetarian school meals in general, including components such as salad and fruit, has been highlighted by some previous studies, suggesting that these meals contribute to increased food waste levels (Byker et al., 2014; Byker Shanks et al., 2017; Donadini et al., 2022; Smith and Cunningham-Sabo, 2014). In addition, plant-based protein sources have been shown to lead to increased plate waste in schools (Lindke et al., 2022). On the other hand, increased acceptance of vegetarian dishes among schoolchildren has also been indicated (Keyzer et al., 2012; Lazor et al., 2010; Lombardini and Lankoski, 2013).

Several previous studies have investigated food waste levels in school catering (Eriksson et al., 2017, 2019; Malefors et al., 2019, 2022b; Östergren and Backlund, 2019). However, large-scale studies investigating possible goal conflicts between high meal acceptance, reduced food waste, and vegetarian options are still scarce. Accurate knowledge on how to develop school lunch menus that provide meals with high acceptance among pupils, while maintaining high sustainability through low levels of food wastage and reduced meat consumption, is essential for transition to a more sustainable food system. Therefore, the aim of the present study was to investigate whether high or low acceptance and the presence of vegetarian meals on the school lunch menu influence food waste levels. A further aim was to gain an in-depth understanding of kitchen staff's perspectives on the wastage associated with school meals and on how the school lunch menu could be adapted to reduce the environmental impact.

2. Material and methods

Mixed methods combining qualitative and quantitative approaches were applied to enable a more complete and comprehensive analysis of the wastage of school meals in relation to their popularity. First, qualitative data from semi-structured interviews (Kvale, 1996) with kitchen staff were used to categorize the level of popularity (level of acceptance) of different meals among schoolchildren. The interviews also aimed to explore kitchen staff's perspectives and experiences regarding food wastage in school catering. These qualitative data were then combined with quantitative food waste data on lunch menus in school canteens. The study design is illustrated in Fig. 1.

2.1. Qualitative method

The interviews were conducted using a semi-structured interview guide. In semi-structured interviews, participants can speak freely about issues that are important to them, allowing for a variety of perspectives to be conveyed, while the interview adheres to the topic through preformulated questions (Kallio et al., 2016). To test the interview guide and allow revision of the interview questions, four pilot interviews were conducted with kitchen staff from two primary schools and one preschool in Stockholm. In these pilot interviews, the kitchen staff were asked partially open-ended semi-structured questions. The interview questions were slightly reformulated based on the results, but without any major changes to the content, resulting in 12 interview questions (see Appendix A).

After completing the pilot interviews, actual data collection was conducted by interviewing school kitchen staff in Uppsala Municipality in March 2022. To recruit participants, the convenience sampling method was used. Those responsible for school meals in the municipality were contacted, and in turn provided a list of suitable contacts among the kitchen staff. In total, 13 kitchen staff members from seven primary and secondary schools participated in face-to-face interviews. The

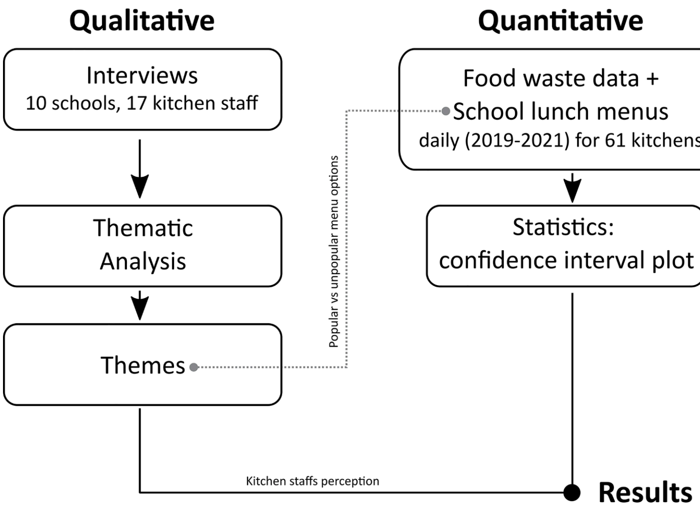

Fig. 1. Study design applied, including qualitative and quantitative methods and procedures used to collect and analyze data.

interviews were conducted in either Swedish or English by two research team members, with each interview lasting approximately 20 min. Questions were asked about (1) popular and unpopular dishes; (2) popular and unpopular vegetarian dishes; (3) pupils' attitudes to school meals; (4) the kitchen's strategies to lower food waste; and (5) the impact of these strategies on the pupils. During the interviews, notes were made using a laptop computer, with pauses to type in the answers when necessary. As both the questions and responses were similar for the pilot and actual interviews, the pilot interview results were included in the final analysis. Thus in total, 17 kitchen staff from one preschool, seven primary schools, and two upper secondary schools in Sweden were represented in the data. Informed written consent was obtained from each participant and the participants were allowed to withdraw their consent at any time. All data were treated confidentially, and the participants were coded to protect their anonymity (Appendix B). During the study, no sensitive personal data were collected from the interview participants and therefore obtaining ethical approval was not necessary.

2.2. Quantitative methods

All food waste quantification data were collected at canteen level by kitchen staff themselves as part of their daily routine. They weighed all food waste generated during lunches according to the standard established by the Swedish Food Agency, (2020), whereby food waste is divided into *kitchen waste* (waste produced in production kitchens), *serving waste* (leftovers from servings that never reach guests' plates), and *plate waste* (guests' unconsumed waste). Because kitchen waste represents a relatively small fraction (8%) of the total food waste generated in Swedish school kitchens, only serving waste (48%) and plate waste (44%) were included (Malefors et al., 2019). Each guest who attends the meals is also counted as part of the food waste quantification work, to calculate the relative indicator 'waste per guest' (in grams). The quantification work took place in 61 school canteens in Uppsala Municipality and the data collected covered the period November 2019 to September 2021. In addition to serving waste and plate waste quantification data, lunch menu data for the same period as the food waste data were obtained from the municipality and used in the analysis.

All data were subjected to a cleaning process in which any doubtful data, such as food waste recorded in grams instead of kilograms, were corrected. The next step was to establish a basis for analyzing the canteens on equal terms, i.e., only data from canteens that quantified the amount of serving waste, plate waste, and guests per day were selected for further evaluation. If a canteen did not quantify one of these parameters on a particular day, all data for that day were discarded, as further explained by Malefors et al. (2019). To enable robust analysis of the key performance indicator 'waste per guest' (g), the median value was used to reduce the impact of outliers or extreme values. Data on the lunch menus, which were served buffet-style and consisted of 1–3 main hot meals per day, mostly with at least one vegetarian option, were combined with the food waste data on a daily basis.

2.3. Analysis

The qualitative data were interpreted using thematic analysis (Braun and Clarke, 2006). The interview transcripts were first translated into English and the translations were then double-checked to ensure their accuracy. The analysis started with reading the data, with the researchers reading the transcripts several times to determine the appropriate codes. The codes were grouped into sub-themes, which were then merged into broad themes. In the coding process, codes and themes were discussed repeatedly to ensure that all researchers shared the same interpretation.

The interview data were also used to categorize the menus. Since the school meals were served buffet-style, food waste quantification data on meal or food item level were not available. Therefore based on kitchen staff's statements in the interviews, the daily lunch menus were categorized into three types: 'high acceptance', 'low acceptance', and days with 'both' high acceptance and low acceptance meal options. The category 'high acceptance' comprised days when only popular options were served, while 'low acceptance' comprised days when only unpopular options were served. Hereafter, the terms high/low acceptance and popular/unpopular are used interchangeably. Furthermore, based on what was served, the menus were classified as days with a 'mixed menu', i.e., with both vegetarian and non-vegetarian meals being served, and days with a 'vegetarian menu', i.e., with solely vegetarian meals being served. The results on the popularity of meals and vegetarian meals were then used as categorization input for the quantitative analysis. The quantitative material used for analysis was based on 9262 observations from 61 kitchens, as summarized in Table 1.

The results are presented as grouped scatter plots with confidence intervals (95% level) comparing food waste quantities between days when popular meals, unpopular meals, or both popular and unpopular meals were served. The food waste plots are further divided into mixed menu and vegetarian menu days. The qualitative and quantitative data were combined in the final analysis.

3. Results

The analysis resulted in three themes: 1) the vegetarian paradox; 2) the waste myth concerning popular school meals; and 3) methods for mitigating food waste. These themes are presented below, with exemplifying quotes and supporting quantitative data when applicable.

3.1. The vegetarian paradox

The opinions about popular and unpopular meal options were similar among kitchen staff at the various schools. According to the kitchen staff, unpopular meal options included vegetarian dishes in general, as well as stews, fish stew, fish gratin, and meals including visible vegetables and mixed ingredients:

> "Strange vegetarian dishes, lentils, vegetables, they [pupils] are afraid of these. Some fish gratin, they [pupils] don't like it." (001)

Meatballs, pasta, spaghetti bolognese, various potato dishes, chicken, hamburgers, lasagna, sausages, and tacos were considered the most popular meal options, but also pancakes, which were vegetarian:

> "Most popular are pancakes, the only dish they don't regard as vegetarian." (001)

Thus, a vegetarian paradox was detected in the material, with kitchen staff claiming that all vegetarian dishes are unpopular but with several vegetarian meal options among the most popular dishes. The most popular vegetarian meal options were pancakes, vegetarian nuggets, vegetarian schnitzel, red lasagna, potato pancakes, vegetarian tacos, and vegetarian soups. Other meal options considered popular, but not mentioned as many times, were falafel, soy sausage, curry with Quorn, and pasta with gorgonzola. Unpopular vegetarian options were vegetarian patties with rice, beans, peas, mixed stews or stews with legumes, lentils, dishes where the vegetables were visible, cabbage pudding, and mushrooms. Some vegetarian dishes, such as vegetarian patties, vegetarian nuggets, stews, soy sausage, and gratin with cheese, divided opinion, as they were considered both popular and unpopular.

Some kitchen staff mentioned unfamiliarity with vegetarian dishes as the reason for pupils disliking these dishes. The kitchen staff also explained that the popular vegetarian dishes, such as pancakes and potato pancakes, were not considered vegetarian, because they did not include any visible vegetables. The kitchen staff reported that the pupils accepted vegetables when served as tacos, nuggets, or lasagna, i.e., in cases where the dishes looked or tasted similar to meat.

> "They like soy sausage, they like vegetarian tacos. They like when it tastes or looks like meat." (008)

Table 1
Numbers of days with menus classified as 'high acceptance meals', 'low acceptance meals' and 'both' high acceptance and low acceptance meals, further divided into days with a mix of vegetarian and non-vegetarian options ("Mixed menu") and days with only vegetarian options ("Vegetarian menu").

	Mixed menu (n)	Vegetarian menu (n)
High acceptance meals	1209	536
Low acceptance meals	1629	488
Both	4018	1382
Total	6856	2406

The kitchen staff also reported that the pupils wanted varied school lunches, especially the salad buffet offering side dishes. These vegetarian meal options were considered popular and included potato salad, pasta salad, "pizza salad" (cabbage mixed with oil, vinegar, pickled peppers and seasoning), and raw vegetables, such as tomato, cucumber, and sweet pepper served in separate serving bowls. However, serving these was not always possible for budget reasons. During winter in particular, it was challenging to offer as large a variety as pupils would like in the salad buffet for cost reasons, according to the kitchen staff.

3.2. The waste myth concerning popular school meals

The interviews revealed that the perception that the most popular school meals generate most waste was commonly held by the kitchen staff. As an explanation, the staff highlighted pupils' behavior of taking too large portions of their favorite food, but then not being able to clear their plates. As a result, more plate waste was generated, in their opinion:

> "The popular dishes are thrown away the most. The least favorite dishes are not wasted as much. Some pupils think they like the food and therefore take more, but it can be wasted because they can't finish it or because they think the taste is not good enough." (001)

This perception that popular dishes result in more waste appears to be a myth. In fact, the quantitative results indicated a lower level of food waste for popular compared with unpopular lunch menus, as illustrated in Fig. 2. On analyzing *serving waste* and *plate waste* combined with lunch menu data, in most cases it was found that unpopular dishes generated more food waste than popular dishes, regardless of whether the menu of the day was mixed or vegetarian. More specifically, days when unpopular dishes were served had significantly higher levels of *plate waste* than days when popular dishes were served. The amount of *serving waste* was also significantly higher on days with unpopular options than on days with popular options when a mixed menu was served.

In the case of mixed menus, popular meals generated 11% less *plate waste* than unpopular meals. In the case of vegetarian menus, analysis of *plate waste* revealed that the amount was 19% higher when unpopular meals were served in comparison with popular meals. In terms of serving waste, on days with a mixed menu, unpopular meals generated 21% more *serving waste* than popular meals. On days with a vegetarian menu, there was no difference in *serving waste* between unpopular and popular meals.

On days with mixed menus, the sum of plate waste and serving waste was 49.5 g/guest when unpopular meals were served, and 41.2 g/guest when popular meals were served indicating a reduction of 17% in food waste. However, on days with a combination of unpopular and popular meals, food waste totaled 44 g/guest, which also indicated a reduction (−11%), on days with a mixed menu. On days with a vegetarian menu, a food waste reduction of 21% was found between days with unpopular meals (49.6 g/guest) and days with both unpopular and popular meals (39.2 g/guest) when plate waste and serving waste were summed up.

3.3. Methods for mitigating food waste

The staff used various methods for mitigating food waste. With some exceptions during the Covid-19, the pupils were serving themselves the amount of food they wished to have, however, the staff tried to encourage pupils to consider their portion sizes by encouraging them to take smaller portions first and come back for seconds later. One school also had a separate line for second servings to reduce queuing time, thereby minimizing the risk of children serving themselves too much on the first occasion, as they know that they would have time to come back for seconds. Another method used for mitigating waste was to use the leftovers as ingredients for other meals on the following day. A third strategy was to change the amount of food prepared, with some kitchens reducing the amount of food they prepared on days when unpopular

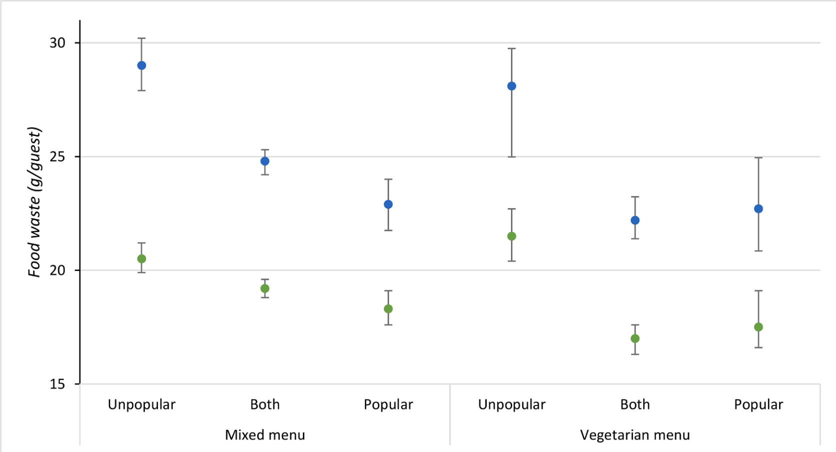

Fig. 2. Food waste levels, divided into serving waste (●) and plate waste (●), of popular and unpopular dishes served in a mixed menu and a vegetarian menu.

dishes were served. To ensure that the pupils had enough food to eat on those days, kitchen staff increased the amount of side dishes, such as baked bread. This strategy was followed because the pupils tended to eat more of the side dishes, instead of the main courses, when unpopular meal options were on the menu:

> "When they [pupils] do not like the food, they eat the side dishes or pasta/rice/potato instead." (011)

To overcome the problem of unpopular visible vegetables, the kitchen staff reported that they simply concealed the vegetables in the dishes, thereby increasing the popularity of such meals:

> "If you can hide the vegetables, they [pupils] eat them; the kitchen tries to hide the vegetables." (001)

Perceptions among the kitchen staff about the level of wastage associated with vegetarian dishes varied, with some stating that vegetarian dishes generated more waste than non-vegetarian dishes and others claiming the opposite or reporting no difference. To increase pupils' intake of vegetarian dishes, one kitchen had used a nudging strategy by changing the order of the lunch buffet to place vegetarian dishes first (Bucher et al., 2016). This move was considered rather effective in increasing pupils' intake of vegetarian dishes, although staff reported that the pupils still preferred non-vegetarian dishes.

Some of the kitchen staff interviewed reported that their methods for lowering food waste had actually worked, while others reported the opposite. A common challenge mentioned during the interviews was difficulty in increasing pupils' interest in reducing food waste on their own, and kitchen staff felt that they needed support from the teaching staff in this regard. According to the kitchen staff, younger pupils usually listened to them more closely, while the older pupils mostly did not take their advice seriously:

> "The younger children listen more and understand more about food waste, especially when you talk to them. The younger pupils also have more teachers eating with them and explaining food waste to them. But the older pupils barely notice or dont care about food waste." (003)

4. Discussion

This study investigated possible goal conflicts between high acceptance of school meals, reduced food waste, and including vegetarian options in Swedish school lunch menus. The results suggested that these goals are not conflicting and that there is scope for serving meals that fulfill all three goals. In fact, the results showed that unpopular lunch menus generated more food waste than popular menus, suggesting that *popular meals* should be favored over *unpopular meals* on school lunch menus. The results also indicated that vegetarian menus did not generate more food waste than mixed menus including meat, and in fact generated less in some cases, suggesting that *popular vegetarian meals* should be encouraged on Swedish school lunch menus. These findings contradict the common perception of popular meals generating the most food waste, which interviews revealed to be widely held among kitchen staff. The perception seemed to be rooted in a common view of pupils taking excessively large portions of the options they liked the most and not being able to finish these portions, resulting in more food waste. While previous studies have identified large portion size as a risk factor for plate waste (Steen et al., 2018), the results obtained in the present study suggest that the common perception that meals with high pupil acceptance generate the most food waste is erroneous.

Our analysis showed that unpopular menus generated more *plate waste* than popular menus, regardless of whether the lunch menu was vegetarian (+23%) or mixed (+12%). This is in line with findings by Thorsen et al. (2015) that *liking* school meals is negatively associated with percentage plate waste among Danish schoolchildren. Moreover, according to a recent survey of 15-year-old pupils in Sweden, success factors for reduced food waste in their opinion are *good food* and *tastiness* (Köhn and Boode Nylander, 2020). The results obtained in the present study contradicted previous findings of greater wastage of vegetarian meals and components (Byker et al., 2014; Byker Shanks et al., 2017; Keyzer et al., 2012; Smith and Cunningham-Sabo, 2014). On days when the lunch menu included meals of high and low acceptance, we found that the amount of plate waste was 13% lower and serving waste was 12% lower on vegetarian days than on days when the menu included meat options (mixed menu) (Fig. 2). We also found that popular vegetarian menus had a similar degree of plate waste as popular mixed menus, but 17% less plate waste than disliked mixed options.

Vegetarian options in general and dishes with visible vegetables were considered by kitchen staff to be low acceptance options among pupils. However, when more specific questions were asked, the interview responses paradoxically revealed that many vegetarian options, such as vegetarian nuggets, vegetarian schnitzel, red lasagna, potato pancakes, tacos, and soups, actually had rather high acceptance among pupils, whereas meals containing legumes, lentils, beans, and mushrooms had low acceptance. This difference between liked and disliked dishes and food components could be partly caused by the food texture preferences of children, which have been found to be a major reason for them rejecting or accepting food (Cappellotto and Olsen, 2021). Interestingly, children living in northern European countries, such as Sweden, have been identified as *hard-likers*, while children living in southern Europe have been identified as *soft-likers* (Laureati et al., 2020). According to Laureati et al. (2020), *hard-likers* have lower consumption of legumes (commonly eaten soft-cooked), but higher consumption of vegetables (often served raw in the north), which could also explain our findings of high popularity of breaded foods (crispy, hard surface) and tacos, and the unpopularity of cooked vegetables, beans, and mushrooms (soft). However, we identified some contradictions in acceptance of certain vegetarian meals, as some options, such as vegetarian patties and nuggets and soy sausages, were considered both liked and disliked. The wider confidence intervals found for vegetarian menus in comparison with mixed menus (Fig. 2) could be due to this contradiction in acceptance of vegetarian meals, supporting the view that some pupils may like vegetarian options while others dislike them. A previous study identified significant differences in school meal liking, including vegetarian meals, based on pupils' sex (Donadini et al., 2022). Interviews with kitchen staff in the present study revealed that pupils' unfamiliarity with vegetarian meals and their perception of vegetarian food as consisting only of vegetables could partly explain the contradictory findings on acceptance of vegetarian options.

In the *vegetarian paradox* revealed by the interview material, several vegetarian meals were reported to be popular. The results also revealed a decreasing trend of food wastage when serving popular school menus instead of unpopular school menus, whether with vegetarian or mixed menus (Fig. 2). While the results demonstrated that serving unpopular school meals leads to a greater amount of food waste, it can also be concluded that serving popular meals is likely to lead to higher food intake among pupils in comparison with unpopular meals. Increasing the frequency of popular vegetarian options on school lunch menus could bring several advantages in addition to reduced food waste, e.g., it would reduce the carbon footprint of school meals and likely lead to more healthy and nutritious school meals. Diets low in greenhouse gas emissions have been found to be as nutritious as diets high in emissions (Bälter et al., 2017). Vegetarian eating patterns may also be associated with a reduced risk of negative health outcomes, including diabetes, ischemic heart disease, and cancer risk (Oussalah et al., 2020). The prevalence of overweight and obesity among children is high and on the rise, so prevention measures are of the utmost importance (Public Health Agency of Sweden, 2019). Overweight and obesity are major contributors to ill health, and are also an environmental burden contributing to metabolic food waste (Sundin et al., 2021; WHO, 2021). The causes of overweight and obesity are complex, but the fundamental cause is considered an energy imbalance between energy intake and expenditure, often caused by so-called obesogenic environments where energy-dense foods are readily available and sedentary lifestyles prevail (WHO, 2021). While high acceptance, or high intake, of school meals could be argued to contribute to overweight, and thus metabolic food waste, school meal schemes have been identified as a key measure in prevention of childhood obesity, through their ability to promote healthy food environments for children (European Commission, 2013). Serving nutritious and increasingly plant-based school meals that are popular among pupils is likely to play an important role in this regard.

Our interviews with kitchen staff uncovered some successful strategies that they use to increase pupils' liking for unpopular vegetarian meals, in an attempt to reduce food waste. One strategy was to hide vegetables in different dishes. Another strategy was to cook vegetarian meals that look and taste similar to popular meat options, such as tacos, nuggets, or lasagna. Since kitchen staff are first-hand observers of pupils' meal acceptance, close co-operation between municipal menu planners and kitchen staff, exploiting the experience and cooking skills of the kitchen staff, could be an important factor for success in developing school lunch menus that meet different economic, environmental, and nutritional goals. However, meeting multiple goals can be challenging, with kitchen staff indicating that they would need help from teaching staff to reduce waste. In particular, the staff regarded older pupils as hard to reach and as generating more food waste, which is in line with previous findings (Eriksson et al., 2017; Steen et al., 2018). Educational meals, where school lunches are integrated with appropriate teaching activities in order to promote healthy eating habits for children (Persson Osowski et al., 2013), are a possible solution warranting further study.

The kitchen staff interviewed in this study applied some food waste mitigation measures with potential implications for the nutrient intake of schoolchildren. Some kitchen staff asked pupils to start with one portion and come back for a second serving, especially when popular meals were served. The intention of the kitchen staff was not to limit food intake by the pupils, but rather to prevent plate waste, but there is a risk that this measure could be misinterpreted by the pupils as a way to restrict their intake (Bjernevall, 2022). Therefore, communications on portion limitations must be very clear, to avoid such misunderstandings and ensure the satiety of schoolchildren. Another food waste mitigation measure was to cook less food and serve more bread and side dishes instead, to ensure satiety of the schoolchildren on days when unpopular meals were on the lunch menu. However, school meals are usually carefully planned, including calculations to ensure that the nutritional requirements of schoolchildren are met (Swedish Food Agency, 2021), and similarly to plate waste, deviating from the plan could have implications for nutrition intake among pupils. This type of measure can be considered as sub-optimizing the goal of school meals, whereas simply replacing unpopular meals with popular meals would likely lead to a more optimal solution.

There were some weaknesses with the present study, e.g., qualitative data on popular and unpopular school meals were obtained from kitchen staff instead of pupils. However interviewing the kitchen staff was also a strength of the study, because of their knowledge and experience regarding food wastage, food service, meal preparation, and school meal acceptance. The categorization of popular and unpopular dishes was based on interviews from only two municipalities in Sweden, which is a possible weakness. However, 17 kitchen staff were interviewed in total and the popularity of dishes was consistent among the interviewees and agreed with previous literature (e.g. Eriksson et al., 2016), so the results are likely to be generalizable. Other limitations were that the interviews were short and not audio-recorded, which may have limited the possibilities to pick up all the quotes during the interviews and in turn may have set some limitations on the thematic analysis.

Swedish school meals are publicly funded and in many cases provided by public organizations, so school catering is steered by political goals where profitability is not the highest priority. There is therefore great potential for the findings in the present study to be incorporated directly into Swedish public food service organizations. Some results can probably also be useful in other countries, as school meals are not unique to Sweden. What policymakers can learn from the present study is that there are ways to avoid the perceived goal conflict between reduced waste, more vegetarian meals, and high acceptance among pupils.

One way to enable school catering to meet multiple goals is to increase the frequency of meals that have high acceptance, have low waste levels, and are vegetarian, which in a Swedish context means e.g., pancakes, vegetarian nuggets, and vegetarian tacos. Meals that have low acceptance, that include meat, and that result in high waste, such as mixed dishes with fish or meat that include visible vegetables could be completely removed from the menu or at least served at a lower frequency. It can of course be argued that schoolchildren should be exposed to a varied diet and encouraged to try new types of foods, which are perfectly reasonable ambitions. However, if there is variation only in what is served, but not in what is eaten, such priorities will not produce the desired results. Therefore, the cooking skills of kitchen staff could be of utmost importance in terms of developing recipes favoring children's sensory preferences, but also applying presentation techniques that appeal to pupils (Liz Martins et al., 2020; Tuorila et al., 2015). Favoring popular meals in school menus could of course increase the risk of menus becoming unbalanced. However, removing for example stews from menus containing fish, beans, or soft-cooked vegetables would not have to mean that these types of ingredients should be excluded from school menus, but they could be cooked or served in some other way instead and thus support the dietary diversity of school menus. Popular meals such as hamburgers, tacos, and meatballs could be prepared with healthier ingredients, such as plant-based meat analogues shown to be higher in dietary fiber and lower in saturated fat in comparison to meat references (Bryngelsson et al., 2022).

An ambition to serve more vegetarian meals of high acceptance would result in pupils tending to generate less waste and eat less meat. Based on the data and results of the present study, we estimate that in approximately 20% of the Swedish school menus, a switch from unpopular towards more popular meals could be made potentially resulting in up to a 2% reduction in overall food waste (420 tons/year). According to a recent forecasting study on food waste levels in 2025 in Swedish school catering, halving the 2016 level could be within reach by 2030 (Malefors et al., 2022a). However, the forecasting model also indicated a possible plateau of 5 g/guest above the target. Therefore, additional measures of different kinds are likely to be needed to ensure reaching the food waste target but attention should also be paid to ensuring high acceptance, and thus adequate intakes of schoolchildren. Removing and modifying the most unpopular meals would be an easy and quick measure to implement. Therefore, the Swedish public school food service has great potential to continue with the trend of serving less meat described by Sjölund (2021) and the trend for lowering food waste described by Malefors et al. (2022a). It would thereby contribute to sustainable development through the actual catering operations and through pupils acting as role models for the rest of society.

5. Conclusions

This study examined whether there is a goal conflict between high acceptance of school meals, reduced meat options, and decreased food wastage. The results showed that school meals with high acceptance were wasted to a lesser extent than meals with low acceptance, including vegetarian options. These results contradict the common perception that popular school meals drive plate waste, which catering staff should regard as a popular myth. A vegetarian paradox was observed throughout the interviews, with vegetarian options reported to be unpopular but with several vegetarian options among the most popular choices. School meals must meet multiple goals, but high pupil acceptance and adequate intake of nutritious school meals must be the highest priorities. Once these priorities are met, other goals, such as meeting environmental targets on reduced food waste and reduced carbon footprint, can be met in a meaningful way. There is no justification to keep on serving unpopular meals in school catering and the focus should instead be shifted to serving popular nutritious meals, including popular plant-based meal options, when striving to develop more sustainable school meal schemes.

CRediT authorship contribution statement

Niina Sundin: Conceptualization, Methodology, Visualization, Data curation, Formal analysis, Writing – original draft. **Christopher Malefors:** Conceptualization, Methodology, Visualization, Data curation, Formal analysis, Writing – review & editing. **Maja Danielsson:** Conceptualization, Methodology, Visualization, Data curation, Formal analysis, Writing – review & editing. **Marina Hardiyanti:** Conceptualization, Methodology, Visualization, Data curation, Formal analysis, Writing – review & editing. **Christine Persson Osowski:** Formal analysis, Writing – review & editing. **Mattias Eriksson:** Conceptualization, Methodology, Visualization, Funding acquisition, Writing – review & editing.

Declaration of Competing Interest

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

Data Availability

Data will be made available on request.

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Appendix A. Interview guide

No.	Interview question
1	What are the pupils' favorite dishes?
2	What are the students' least favorite dishes?
3	What food components in the lunch menu do the schoolchildren like the most? (Such as salad)
4	What dishes/ food components most often end up in the trash?
5	Do the students eat less or more when their favorite dishes are served?
6	Do students eat less or more when their least favorite dishes are served?
7	What kind of vegetarian dishes are served?
	How popular are vegetarian dishes in comparison with other dishes? Is there a difference in popularity within vegetarian dishes?
	Are vegetarian dishes wasted more or less than other dishes? How much more/less? Why is that?
8	Does your school measure food waste?
	Does the school have any actions to lower food waste? If yes, what are these actions?
9	Do the students change their behavior when you remind them about lowering food waste?
	Additional questions about the school
10	How old are the students at the school?
11	Is the food cooked here at the school?
12	Are there any questions from the kitchen staff?

Appendix B

Interview code	Type of interview	Type of school
001	Pilot interview	Primary school
002	Pilot interview	Primary school
003	Pilot interview	Preschool
004	Pilot interview	Primary school
005	Interview	Upper secondary school
006	Interview	Primary school
007	Interview	Primary school
008	Interview	Primary school
009	Interview	Primary school
010	Interview	Primary school
011	Interview	Primary school
012	Interview	Primary school
013	Interview	Upper secondary school
014	Interview	Primary school
015	Interview	Primary school
016	Interview	Primary school
017	Interview	Primary school

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From plate to waste: Composition of school meal waste and associated carbon footprint and nutrient loss

Niina Sundin [a,*], Runa Halvarsson [a], Silvia Scherhaufer [b], Felicitas Schneider [c], Mattias Eriksson [a]

[a] Department of Energy and Technology, Swedish University of Agricultural Sciences, Box 7032, 750 07, Uppsala, Sweden
[b] Department of Water, Atmosphere and Environment, University of Natural Resources and Life Sciences, Muthgasse 107, 1190, Vienna, Austria
[c] Thünen Institute of Market Analysis, Bundesallee 63, 38116, Braunschweig, Germany

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ABSTRACT

Food waste significantly impacts the environment and nutrient availability. In Sweden, public meals generate 33,000 tonnes of food waste annually, with elementary schools contributing 9,200 tonnes. A composition analysis of plate waste from 4913 meals in two elementary schools in Uppsala, Sweden identified the wasted food components and quantities. This assessment aimed to gauge the embedded climate impact and nutrient loss. Findings revealed a carbon footprint of 1.0 kg CO2e/kg plate waste. Despite staple foods (potatoes, pasta, rice) being wasted the most (59 %), meat waste constituted the largest portion of the carbon footprint (61 %), despite being wasted the least (10 %). Plate waste was nutrient-dense, containing 4.8 MJ energy/kg and significant levels of protein (57 g/kg), and fiber (19 g/kg). To enhance the sustainability of school meal programs, tailored food waste prevention strategies in Swedish school canteens are recommended to mitigate their environmental impact and preserve valuable nutrients for children's nourishment.

1. Introduction

Food waste is a problem with far-reaching consequences for the planet and global population. Approximately one-third of all food produced globally is either lost or wasted, leading to negative economic, environmental, and social impacts. Global food wastage costs 2.6 trillion USD annually and accounts for 8–10 % of global greenhouse gas emissions (FAO, 2014; UNEP, 2021). However, this estimate does not include the carbon footprint of land use change and residues elimination and/or treatment making the actual proportion likely higher. Food production also dramatically contributes to eutrophication, acidification, and biodiversity loss (FAO, 2014; Scherhaufer et al., 2018). Six out of nine planetary boundaries have already been exceeded on the global scale (Richardson et al., 2023), with current food production and management practices significantly contributing to this problem (Springmann et al. 2018). Although food waste can be utilized as an energy source through anaerobic digestion, thereby lowering the climate impact of the waste, it is more important to avoid producing food that will be wasted in the first place, due to the enormous environmental impact of food production (Scherhaufer et al., 2018). For example, within the European Union (EU), the majority (73 %) of the climate impact from food waste is estimated to originate from the production stage (Scherhaufer et al., 2018). Food loss and waste also have significant food security implications. Food insecurity is on the rise, with up to 3.1 billion people around the world now unable to afford a healthy diet and with 828 million suffering from hunger (FAO et al., 2022). In parallel, a significant level of nutrient loss embedded in global food waste is potentially affecting the health and wellbeing of people and communities (Chen et al., 2020). Moreover, consumer wastage of essential nutrients has been shown to be correlated with nutritional deficit in a typical American diet (Spiker et al., 2017). Thus, due to the devastating socioeconomic and environmental costs, reducing food loss and waste is one of the key measures to achieve sustainable food systems, which are a high priority on the public agenda and included in United Nations Sustainable Development Goal (SDG) 12.3, which aims to halve food waste per capita by 2030 (United Nations, 2015).

The EU is committed to reducing its food waste in order to reach SDG 12.3, through various policies, targets, and action plans (European Commission, n.d.). Within the EU, 88 million tonnes of food waste are generated annually, corresponding to 186 million tonnes of CO_2e, representing 16 % of the EU food system's climate impact (Scherhaufer et al., 2018; Stenmarck et al., 2016). As an EU member state, Sweden has implemented EU goals and also national goals to combat food waste. The interim target states that total food waste in mass per capita in Sweden

* Corresponding author.
E-mail address: niina.sundin@slu.se (N. Sundin).

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should be reduced by 20 % between 2020 and 2025. However, progress is slow and there are uncertainties about whether this target will be reached on time. Thus, unacceptable levels of food waste continue to be generated throughout the world and Sweden is no exception, with approximately 1.1 million tonnes of food wasted in 2020 (Hultén et al., 2022; UNEP, 2021). Although public meals represent only a fraction of total food waste in Sweden (33,000 tons, with 9200 tonnes generated by elementary schools in 2020), reducing this type of waste is of the utmost importance for several reasons (Malefors et al., 2022a). First, most of the food waste from public meals consists of serving and plate waste, i.e., edible food that has undergone resource-intensive preparation (Malefors et al., 2019; Read et al., 2020). Wasting food in school catering also represents a missed opportunity to nourish school children, as school meals in Sweden are required by law to be nutritious and studies have highlighted gaps in nutrient intake by Swedish school children (Swedish Food Agency, 2022). Additionally, food waste reduction measures are necessary throughout the whole food supply chain, involving all stakeholders at all geographical levels, to reach SDG 12.3 and achieve a sustainable food system (Reynolds, 2022).

Previous studies suggest that plate waste[1] accounts for the second highest proportion of food waste in Swedish public catering, after serving waste (Eriksson et al., 2017; Malefors et al., 2022a; Persson Osowski et al., 2022; Silvennoinen et al., 2015). The amount of serving waste have been found to be especially high in satellite kitchens, due to low flexibility to adjust the amount of food produced, whereas kitchen type does not have a significant impact on the amount of plate waste (Eriksson et al., 2017; Persson Osowski et al., 2022; Steen et al., 2018). This makes it possible to reduce plate waste irrespective of the kitchen type. However, reducing plate waste generated by guests self-serving from a buffet is often seen as challenging by kitchen staff (Sundin et al., 2023), whereas reducing kitchen and serving waste may be easier as waste prevention measures can be directly integrated into work routines, such as improved menu planning and using leftovers from a buffet in warm meals on the following day (Swedish Food Agency, 2020).

In Sweden and many other countries, school meal schemes are a crucial route for providing immediate nourishment to children, while educating them about sustainable eating habits for the future (GCNF, 2022; Swedish Food Agency, 2022). Since 2011, the Swedish School Law mandates nutritious school lunches, aligned with national guidelines initially issued in 2015 based on the Nordic Nutrition Recommendations to facilitate that school meals are also eco-smart, i.e., increasingly plant-based and associated with reduced food waste (Swedish Food Agency, 2022). Annually, Swedish schools serve 260 million meals, funded by local taxes, with efforts over the past decade enhancing food quality and chef skills in school kitchens. Because meals must meet nutritional standards, food waste cannot simply be reduced by decreasing production if wastage is not caused by overproduction, as each school child has the right to receive a school meal that is nutritionally balanced, fulfilling 30 % of their daily energy and nutrient requirements. Plate waste may in fact serve as an indicator that nutritious food is left uneaten, resulting in nutrient losses and unnecessary environmental burdens.

Quantifying food waste is the first step towards achieving food waste reductions, and Sweden has achieved a high degree of success in quantification (Malefors et al., 2022a), but some factors are yet to be resolved. School meals comprise diverse food components such as carbohydrates (potato, pasta, rice), proteins (legumes, fish, chicken, beef), vegetables, bread, fruit, and dairy. Knowledge of the components is common, facilitating the assessment of carbon footprint and nutrient composition of the meals served. While some studies have investigated the components of serving waste in Swedish schools (Eriksson et al., 2017), only few have analyzed the components of plate waste (Silvennoinen et al., 2015), resulting in uncertainties regarding the degree to which various food components are wasted by school children. The carbon footprint and nutrient losses from school meals could differ from the carbon footprint and nutrient content of the served meals, and often rely on estimates or remain unknown (Swedish Food Agency, 2020). This discrepancy can lead to uncertainties in evaluating food waste prevention measures and their sustainability impacts, crucial for policymakers in prioritizing prevention actions (Caldeira et al., 2019). Better knowledge of wasted components would aid in crafting tailored food waste prevention measures, potentially vital for achieving further reductions to meet the target of halving food waste (Malefors et al., 2022a).

The aim of the present study was to fill this research gap by examining the composition of plate waste discarded from 4913 school meals at two elementary schools in Uppsala Municipality, Sweden, with the focus on calculating the carbon footprint and nutrient losses associated with plate waste. The intention was to gain valuable insights into the food components that are wasted instead of being eaten, and the environmental and social implications for school meal schemes.

2. Material and methods

2.1. Study design and material

Plate waste from two elementary school canteens in Uppsala, Sweden, serving pupils aged 6–9 years was quantified and analyzed for its composition during a two-week period in spring term 2023. The selected schools were considered representative samples in Sweden, with a rate of plate waste generation of 27 g/guest close to the national average, and situated within a socioeconomic context reflective of the majority of the Swedish populace, encompassing 60 % of the population. The inclusion criterion for school canteens was maximum 10 kg of plate waste generated per day, making it possible to conduct composition analysis. The participating school canteens are referred to hereafter as canteen A and canteen B.

Canteen A had previously participated in the research project LOWINFOOD in 2022, where it tested waste-tracking devices and educational meals as food waste reduction measures, whereas canteen B had not recently conducted any specific interventions to reduce food waste. Both canteens have a long track record of measuring their food waste and both have satellite kitchens receiving their meals *hot, fully prepared, and ready to be served* from a larger school canteen nearby. Both canteens also have the same six-week rolling menu (Table A.1 in Appendix), of which the two-week observation period was a representative sample in terms of types of meals included (vegetarian, fish, beef, pork, or chicken with potato, pasta, or rice). In addition to the main meals on the menu, a salad buffet comprising vegetables and fresh fruit, such as apples, carrots, broccoli, and olives, as well as bread and milk is provided daily during the lunches. Canteen A uses leftovers from the previous day to reduce its serving waste, and thus provides a slightly larger selection in its buffet than canteen B. Canteen B relies more on its meal planning system when deciding on the amounts of food components to be served. All food is served in a buffet and children help themselves, with the possibility to take second helpings. At the time of the observation, there were no limitations on the amount of food that children were allowed to serve themselves.

Canteen A has about 300 daily guests and canteen B has approximately 320 guests, including pupils and the teaching staff. Both canteens have established routines in place to create a calm meal environment during lunchtime, starting with an enforced 10-minute silence supervised by a teacher. Canteen A serves lunch from 11:00 to 13:00 h, giving all classes 30 min to eat. In canteen B, lunch is served from 10:40 to 12:30 h, where grades 1–3 have 20 min to eat and grade 0 has 30–40 min.

[1] Plate waste refers to everything that a guest has left on their plate, comprising edible food, inedible food such as peels and bones, and other waste, such as napkins (Malefors et al., 2019).

2.2. Data collection

Data were collected for eight days in total, from both canteens over a two-week period. The dates of waste collection were 11–14, 17–19, and 21 April 2023. No plate waste was collected for practical reasons on 20 April, as soup was on the menu, or on 10 April, due to a public holiday. Data collection included all plate waste generated during the school lunches in the canteens, but excluded beverages and any other food waste such as kitchen and serving waste or food waste from breakfast. Both canteens supplied the researchers with their plate waste in plastic bags taken from bins used to collect the plate waste disposed of by guests during school lunches. A plastic container was used to provide a stable resting surface for these plastic bags during transport, to avoid unnecessary mixing of the contents. Waste from canteen B was collected at around 12:30 and taken by foot to a nearby sorting site, while waste from canteen A was collected at around 13:00 and transported by bus to the sorting site. Quantification and composition analysis were conducted on the day of collection.

2.3. Quantification and composition analysis

Quantification commenced by weighing the plastic bags containing the total plate waste and deducting the mass of the plastic bags. An electronic balance with 0.01 kg accuracy was used for weighing (Fig. 1). All results were recorded on a pre-prepared Excel sheet.

In waste composition analysis, different food waste components, such as pasta, chicken, vegetables, and bread, were sorted by hand into plastic containers. On the first day, degree of separation of the plate waste was decided. Complete separation was not possible due to some waste being in liquid form (e.g., sauces) and mixed form (rice with tiny pieces of vegetables). In such cases, sauces and inseparable vegetables were categorized as the main component (see Table A.2 in Appendix for a complete list of waste component categories). The plate waste was categorized into *edible* or *inedible food waste*, where inedible food waste comprised fruit peel and cores, and eggshells. Occasional napkins and spread packages that had accidentally ended up in the food waste bin were separated out into the category *other*. After the sorting process, the plastic containers containing the various plate waste components were weighed one by one, using a tare function on the electronic balance in between each weighing. The waste category with the largest volume, usually the staple food component of the day such as rice or potatoes, was left in the plastic bag for weighing. The mass of the plastic container/bag was deducted, to give the net mass of each waste fraction. The containers were cleaned at the end of each day, to ensure that no food waste was carried over to quantification on the following day.

Fig. 1. Electronic balance weighing a plastic container of plate waste consisting of mixed vegetables. Fotograph Halvarsson R., (2023).

In carbon footprint and nutrient loss calculations on the plate waste, the quantification data were aggregated from daily mass to total net mass per waste category and canteen.

2.4. Carbon footprint calculations

To assess the climate impact of the plate waste, carbon footprint calculations were conducted based on the composition data obtained and emission factors from the RISE Climate Open List (RISE, 2022), which reflect average Swedish food consumption. Currently, the environmental impacts caused by the average Swedish food consumption exceed several boundaries based on the EAT-Lancet framework, including per capita greenhouse gas emissions (Moberg et al., 2020).

The emission factors were presented as kg CO_2e per kg of food, from cradle to producer gate, excluding packaging. For imported food products, transport to Sweden was also included. Other emission sources, such as distribution, storing, cooking, and cooling food, were excluded. Since the emission factors were expressed for uncooked foods, except for bread, some of the plate waste data had to be converted from cooked weight to uncooked weight using average literature values (KF och ICA provkök, 2000). In particular, the waste categories comprising rice, pasta, and Bolognese sauce (beef) were converted, due to large differences between uncooked and cooked weight.

For some waste components, the exact carbon footprint was not included in the RISE Climate Open List (RISE, 2022), and values that were the closest option had to be used. For example, the carbon footprint for *cheese* was used to represent both feta cheese and cottage cheese. To obtain a carbon footprint for the category *mixed vegetables*, an average carbon footprint was calculated using the values for *spinach, green peas, tomatoes, iceberg lettuce, chickpeas,* and *lentils*, which are included in the RISE Climate Open List (RISE, 2022).

After calculating an approximate carbon footprint per waste category and canteen, the results were aggregated to total carbon footprint per waste category and then to total carbon footprint of food waste. The waste category *inedible food waste* was included in the carbon footprint calculation, while the category *other* was excluded. The total carbon footprint was then divided by the total mass of plate waste that the canteens generated, to obtain carbon footprint per kg plate waste.

2.5. Nutrient calculations

To assess the nutrient loss embedded in plate waste, nutrient calculations were conducted based on composition data obtained for the edible fraction of the plate waste, using Nutrition Data (2023) software. The energy, macronutrient, micronutrient, and dietary fiber contents of the plate waste were calculated as total values for the data collection period, in order to express them as mean values per kg plate waste and per guest (by dividing the total values by the total amount of plate waste and the total amount of guests, respectively). Further, the macronutrient content was expressed as energy percent (E%) values, and the micronutrient content as nutrient density value (per MJ), where the mean nutrient values per kg plate waste were divided by the mean energy content per kg plate waste. The number of wasted nutrient days (WND) per kg plate waste, and per canteen and day, during which the plate waste met 30 % of the daily recommended intake (RI) values of the school children (since school meals are required by law to provide 30 % of the daily nutritional needs of children) were calculated. This was done by dividing mean energy and nutrient values by 30 % RI values for children aged 7–10 years with an average physical activity level, according to Nordic nutrition reference 2023 values (Nordic Council of Ministers, 2023).

2.6. Statistical calculations

To evaluate whether there were statistical differences between canteen A and B in terms of the total amount of plate waste and the amounts of the food categories that were wasted, two-sample Student *t*-tests were conducted in Excel. Additionally, Excel was used to calculate totals, mean values, and standard deviation for the number of portions, the amount of plate waste, and the amount of plate waste per portion. To calculate the amount of edible waste, the mass of *inedible food waste* and *other* were subtracted from the total waste. Plate waste as a percentage of total food served was calculated based on the production figures obtained from the two canteens.

3. Results

3.1. Amount of plate waste

The total amount of plate waste collected from canteens A and B during the 8-day collection period was 133.2 kg, of which 125.6 kg (94 %) was edible food waste, 6.4 kg (5 %) inedible food waste, and 1.2 kg (1 %) other type of waste, such as napkins. Total average plate waste was 8.3 kg per canteen and day, and 27 g per guest. Plate waste amounted to approximately 12 % of total food served (1154 kg). There was no statistically significant difference in the amount of plate waste at canteen A and canteen B (p = 0.390). A breakdown of the results per canteen is provided in Table 1.

3.2. Plate waste composition

The food categories wasted in the greatest amounts (of the total waste) were pasta (28 %), potatoes (19 %), rice (12 %), and vegetarian meal options (12 %). Animal-based components, such as pork (1.6 %), beef (1.8 %), and chicken (2.2 %), were among the least wasted categories. An aggregated breakdown of the total results (in kg) and results in kg/per canteen is presented in Table 2 (for a more detailed breakdown, see Table A.2 in Appendix). There was no statistically significant difference in the composition of plate waste between canteen A and B (p = 0.880).

Table 1
Number of guests, amount of plate waste, and amount of plate waste per guest at school canteen A and canteen B. Mean ± standard deviation (SD) for the observation period are also shown.

Canteen	Date	No. of guests	Plate waste (kg/day)	Plate waste (% of prepared food)	Plate waste per guest (g/day)
A	11 April	320	7.6	12	24
	12 April	342	9.6	15	28
	13 April	306	9.5	11	31
	14 April	278	8.0	13	29
	17 April	261	7.8	11	30
	18 April	283	9.5	11	34
	19 April	290	10.4	12	36
	21 April	297	6.6	9	22
	Mean ± SD	294 ± 26	8.7 ± 1.3	12 ± 1.7	29 ± 5
B	11 April	317	6.8	12	21
	12 April	312	9.5	13	31
	13 April	324	9.9	13	31
	14 April	310	6.5	10	21
	17 April	309	8.9	14	29
	18 April	315	8.3	10	26
	19 April	325	7.7	11	24
	21 April	324	6.5	9	20
	Mean ± SD	316 ± 7	8.0 ± 1.3	12 ± 1.8	25 ± 4

Table 2
Breakdown of the food categories in plate waste, expressed as kg per school canteen and total kg, and CO_2e for the observation period.

Food category	Canteen A (kg)	Canteen B (kg)	Total (kg)	Total (CO_2e)
Pasta	19.2	17.8	37.1	10.6
Potato	12.0	13.1	25.1	2.5
Rice	8.0	8.1	16.1	18.1
Chicken	1.4	1.5	2.9	6.1
Pork	1.1	1.0	2.1	9.0
Beef	1.2	1.2	2.4	54.7
Fish	2.5	2.7	5.2	7.8
Cheese	0.1	0.0	0.1	0.6
Eggs & Pancakes	0.9	0.0	0.9	1.0
Vegetarian options	7.0	8.6	15.6	7.8
Mixed vegetables[1]	8.5	5.8	14.3	5.7
Bread	2.1	1.5	3.7	1.5
Inedible FW	4.0	2.4	6.4	1.4
Other	0.8	0.4	1.2	n/a

[1] In addition to vegetables such as broccoli, tomato, and lettuce, the mixed vegetable category comprised olives, carrots, bell peppers, beans, and chickpeas served in a salad buffet.

3.3. Carbon footprint

Total plate waste over the 8-day collection period generated approximately 127 kg CO_2e, corresponding to approximately 1.0 kg CO_2e per kg plate waste or 0.026 kg CO_2e per guest. A breakdown of the total carbon footprint per food waste category is presented in Table 2. The carbon footprint was based on data calculated from cradle to gate (including transport to Sweden), i.e., excluding emissions related to storage and cooking at the canteens.

The wasted food category with the highest carbon footprint, although wasted almost the least in terms of mass, was beef, representing 43 % of the total carbon footprint (

Fig. 2. Total amounts of the wasted food categories (kg) during the observation period (inner circle) and proportion of total carbon footprint (%) per wasted food category (outer circle).Wasted rice had the second highest carbon footprint (14 % of the total carbon footprint), and pasta was third (8 %). The food categories with the lowest carbon footprint, although among the most wasted in terms of mass, were potatoes (2 %), vegetarian meal options (6 %), and mixed vegetables (5 %).

Staple foods such as pasta, potato, and rice comprised 59 % of total plate waste, but only 24 % of the total carbon footprint. On the other hand, animal-based foods (chicken, pork, beef, fish, cheese, and also eggs and pancakes) were wasted to only a minor degree, corresponding

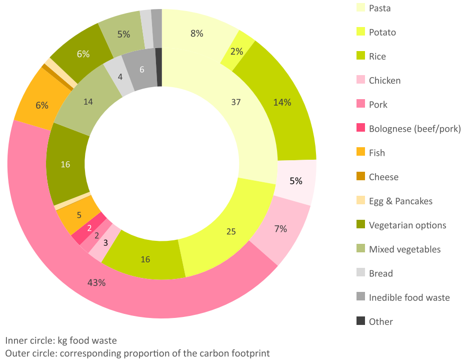

Fig. 2. Total amounts of the wasted food categories (kg) during the observation period (inner circle) and proportion of total carbon footprint (%) per wasted food category (outer circle).

to 10 % of total plate waste, but were responsible for 63 % of the total carbon footprint.

3.4. Nutrient losses

3.4.1. Energy and macronutrients

To assess the nutrient loss embedded in plate waste, nutrient calculations were conducted on the edible part of the plate waste, which contained approximately 4.8 MJ energy/kg plate waste, or 0.13 MJ/guest. The protein, carbohydrate, and fat content per kg plate waste was 57 g, 171 g, and 22 g, respectively (Table 3). Moreover, the plate waste contained 20 E% of protein, 62 E% of carbohydrates, and 18 E% of fat, reflecting a balanced and protein-rich macronutrient content. In terms of WND, each kg of plate waste met the energy needs of two children and the protein needs of seven children.

3.4.2. Micronutrients

Overall, the results indicated considerable nutrient loss as the plate waste was micronutrient-dense, with all except four micronutrients (vitamin D, folate, iron, calcium) meeting or exceeding the recommended micronutrient density for dietary planning (Nordic Council of Ministers, 2023). The plate waste was high in e.g., dietary fiber (3.9 g/MJ), and vitamins A (89.6 RE/MJ), K (21.0 µg/MJ), C (12.9 mg/MJ), and B_6 (0.2 mg/MJ). Assessment of number of WND indicated micronutrient losses of up to 11 days per kg plate waste (Table 4). On average, the plate waste from the canteens could have met the daily micronutrient needs of 4–94 school children, depending on micronutrient (Table 4).

4. Discussion

The composition of plate waste generated from school lunches served in two Swedish elementary schools was analyzed for its carbon footprint and embedded nutrient loss. The results showed that the average carbon footprint (approximately 1.0 kg CO_2e/kg plate waste) was lower than previously estimated (approximately 1.6 kg CO_2e/kg plate waste), since it contained a high proportion of staple foods and plant-based food components. The staple foods that were wasted the most represented 59 % of the total plate waste, but only 24 % of the total carbon footprint. Conversely, animal-based foods were wasted only to a minor degree, corresponding to 10 % of the total plate waste, but were responsible for 63 % of the total carbon footprint. Despite the low proportion of animal-based foods in the plate waste, the results indicated considerable loss of protein (57 g/kg plate waste) and other valuable nutrients, such as dietary fiber (19 g/kg plate waste) and vitamin C (63 mg/kg plate waste). Each of the two school canteens studied could have met 30 % of the daily energy requirements of 18 school children/day if the plate waste had been consumed instead of wasted. Similarly, the plate waste contained enough protein to meet 30 % of the daily requirements of 61 children and the dietary fiber requirements of 28 children.

Table 3
Energy and macronutrient content of the plate waste.

Energy & macronutrients		Per kg plate waste	Per guest	E %	WND[a] Per kg plate waste	WND[1] Per canteen/ day
Energy	MJ	4.8	0.1		2	18
Protein	g	57	1.5	20	7	61
Carbohydrates	g	171	4.6	62		
Fat	g	22	0.6	18		
SFA*	g	9	0.3			
MUFA*	g	7	0.2			
PUFA*	g	3	0.1			

[a] Wasted nutrition days (WND), i.e., number of days the wasted food met 30 % of the recommended daily intake of the children (since school meals must meet 30 % of children's daily dietary requirements), relative to number of school children/day.

* SFA, saturated fatty acids; MUFA, monounsaturated fatty acids; PUFA, polyunsaturated fatty acids.

Table 4
Micronutrient content of the plate waste.

Micronutrient		Per kg plate waste	Per guest	Per MJ	WND[a] Per kg plate waste	WND[a] Per canteen/ day
Vitamin A	RE	433	11.6	89.6*	3	27
Vitamin D	µg	1	0.04	0.3	0	4
Vitamin E	mg	5	0.14	1.0*	2	16
Vitamin K	µg	102	2.7	21.0*	11	94
Vitamin B_1	mg	1	0.02	0.2*	3	25
Vitamin B_2	mg	1	0.02	0.1*	2	18
Vitamin C	mg	63	1.7	12.9*	7	58
Niacin	NE	24	0.7	5.1*	7	57
Vitamin B_6	mg	1	0.03	0.2*	4	33
Vitamin B_{12}	mg	1	0.03	0.3*	2	14
Folate	µg	170	4.6	35.1	3	24
Iodine	µg	290	7.8	60.0*	10	81
Phosphorus	mg	825	22.2	170.6 *	6	52
Iron	mg	5	0.14	1.1	2	16
Calcium	mg	224	6.0	46.3	1	8
Magnesium	mg	184	4.9	38.1*	3	22
Selenium	µg	29	0.8	6.0*	2	20
Zinc	mg	6	0.2	1.2*	3	21
Fiber	g	19	0.5	3.9*	3	28

* Value meeting or exceeding the recommended nutrient density for diet planning according to the Nordic Nutrition Recommendations.

[a] Wasted nutrition days (WND), i.e., number of days the wasted food met 30 % of the recommended daily intake of the children (since school meals must meet 30 % of the children's daily dietary requirements), relative to number of school children/day.

While the carbon footprint and nutrient loss embedded in food waste generated from school canteens have been under-researched to date, our results were in line with those of a previous study conducted in Sweden (Engström and Carlsson-Kanyama, 2004). In a two-day investigation period in that study, staple foods made up the largest fraction of plate waste, while meat and fish were wasted the least. A study in Finland investigating food waste from 23 schools and day-care centers during a five-day period found overall similar plate waste composition as in our study, but lower percentage wastage of vegetarian meal options (Silvennoinen et al., 2015). However, our results regarding the vegetarian option may be uncertain, since the observation period included only one vegetarian day in the menu, although one day per week in the six-week rolling menu is exclusively reserved for vegetarian meal options. It is also possible that the pupils disliked the vegetarian option was served on the vegetarian day observed (vegetarian lasagna), as quantification of vegetarian options from the other seven observation days indicated lower amounts of plate waste. According to a previous study of popular vegetarian meal options in Swedish elementary schools, these meals do not generate large amounts of waste (Sundin et al., 2023).

Our analysis revealed nutrient loss embedded in the plate waste, which was not surprising since Swedish school meals must be nutritious by law and are thus likely to result in nutritious food waste. However, considering the increasing trend for serving more plant-based school meals, which has also been adopted by school canteens in Uppsala, Sweden (Sjölund, 2021), the high protein density of the plate waste despite the low share of animal-based plate waste was an interesting finding. A common public concern is whether school meals contain enough protein when increasing proportions of vegetarian food options are served in schools, replacing meat options (Sydöstran, 2018; Uppsala Nya Tidning, 2022). However, according to the latest national dietary survey, children in Sweden have satisfactory intake of protein and instead too low intake of dietary fiber (1.8 g/MJ, compared with a recommended 3 g/MJ), which is related to their low intake of fruit and vegetables, approximately half the recommended amount of 400 g/day (Swedish Food Agency, 2003). A previous study investigating Swedish school children's energy and nutrient intake from school meals found significant gaps in intake of energy and various nutrients, including dietary fiber (Osowski et al., 2015). Thus if food waste reduction strategies result in a greater proportion of school meals served being eaten, rather than generating plate waste rich in dietary fiber (3.9 g/MJ) and vegetables, this could play an important role in filling gaps in children's nutrient intake. As suggested by previous studies, placing nutrition education on the curriculum for school children or providing them with educational school meals could help tackle food waste and simultaneously improve the dietary habits of school children (Martins et al., 2016; Persson Osowski et al., 2022).

In Sweden, the estimated carbon footprint per kg of food waste is approximately 1.6 kg CO_2e (Swedish Food Agency, 2020), a value based on findings in a study analyzing the carbon footprint of perishable food products from Swedish supermarkets (Scholz et al., 2015), in the absence of other data. We found a carbon footprint for school plate waste of 1.0 kg CO_2e, which is significantly lower than the value reported by the Swedish Food Agency. The difference may be explained by findings that 85 % of the wasted mass from Swedish supermarkets comprises fresh fruit and vegetables, and that the remaining 15 % comprises animal-based products (Scholz et al., 2015), indicating a difference in waste composition in comparison with school canteens. Thus, more studies are needed on the carbon footprint of food waste, as food waste composition can vary greatly between sectors and therefore have different climate impacts.

On comparing the plate waste amounts observed in the present study to global findings, it can be noted that the Swedish elementary schools assessed performed admirably. According to Dou and Toth (2021), who reviewed 18 studies focusing on plate waste and examined 23 datasets encompassing preschools, primary schools, and elementary schools, median plate waste in these establishments is 80 g/meal. In contrast, we found average values of 29 and 25 g per guest for the two canteens studied. Previous studies have reported total food waste quantities of up to 79 g/guest from school canteens in Sweden (Engström and Carlsson-Kanyama, 2004; Eriksson et al., 2017; Malefors et al., 2022a). In elementary schools, average total food waste in 2020 was 42 g per guest (Malefors et al., 2022a).

Various factors affect school meal wastage, such as peer influence, portion sizes, dish popularity, meal sensory attributes, stressful eating environment, and lunch duration (Blondin et al., 2015; Byker et al., 2014; Cohen et al., 2013; Cordingley et al., 2011; Martins et al., 2016; Painter et al., 2016; Piras et al. 2023; Sundin et al., 2023). The influence of schoolchildren's age on plate waste yielded mixed results; while Steen et al. (2018) observed increasing plate waste with age, Cordingley et al. (2011) and Niaki et al. (2017) reported the opposite trend. The observed two canteens had introduced some food waste reduction measures, such as creating a calmer food environment with a 10 min silence and allowing enough time for second helpings, which have been proposed as possible solutions to reduce plate waste in public catering (Swedish Food Agency, 2020). Those solutions can be assigned to actions of food waste prevention which is top priority of the food waste hierarchy (European Commission, 2020). However, the quantification results showed room for improvement, as approximately 12 % of the food served became plate waste. From a strict climate impact perspective, preventing food from being wasted has the most effect for greenhouse gas reduction. Food waste reduction through prevention or reuse was found to be more effective for reaching climate targets (−4.2 kg to −1.3 kg CO_2e per kg food waste), than food waste recycling (material recycling: −0.06 kg to 1.2 kg CO_2e per kg food waste; nutrient recycling: -0.13 kg to 0.09 kg CO_2e per kg food waste; energy recovery: -0.15 kg to −0.002 kg CO_2e per kg food waste) (Albizzati et al., 2021). Similarly, animal-based plate waste would be an effective solution for greenhouse gas reduction, although this would not significantly reduce the overall waste and its associated environmental impacts, or the loss of valuable nutrients. However, there is a growing trend in Sweden for serving more climate-smart meal options and reducing animal-based foods in public catering. Currently the average carbon footprint for the meals served by Uppsala Municipality is 1.5 kg CO_2e per kg purchased food corresponding to 0.5 kg CO_2e per portion with ongoing efforts to achieve a carbon footprint of 1.25 kg CO_2e per kg purchased food by 2030, in line with the Paris Agreement (Uppsala Municipality 2023). This development will likely reduce the carbon footprint of plate waste even if the total amount of food waste is not reduced. Meanwhile, information campaigns could be used to teach school children about the climate impact of food systems and food waste, a measure found previously to be effective in reducing waste (Engström and Carlsson-Kanyama, 2004; Malefors et al., 2022b; Mariam et al., 2020).

For the multiple goals of school meal schemes (nourishing children, environmentally friendly, low waste) to be met in a meaningful way, a fundamental requirement is that all school lunches served are eaten, as highlighted in a previous study (Sundin et al., 2023). To achieve this, school lunches need to be liked by the children. Therefore, reducing unpopular meals and increasing popular nutritious meal options on the school lunch menu has been suggested as a simple, but likely effective, measure (Sundin et al., 2023). However, not all meal options will be equally liked by all children, likely resulting in some plate waste. A recent study found that approximately 60 % of plate waste in Swedish school canteens is generated by 20 % of guests and that 40 % of guests do not waste any food (Malefors et al., 2024). An effective strategy could therefore be to nudge more target groups of school children by awareness-raising interventions, although this is yet to be confirmed by future studies. Some previous studies have shown positive results in terms of reducing plate waste due to educational campaigns, although whether the effects remain long-term is still unclear (Antón-Peset et al., 2021; Malefors et al., 2022b). In the case of plate waste caused by oversized portions, changing the size or shape of plates can be an effective measure to reduce food waste (Reynolds et al., 2019; Richardson et al., 2021). Similarly, reducing the size of serving spoons for potato, pasta, and rice components could be another tailored and yet simple food waste reduction measure targeting specific food components that are wasted the most, but further studies are needed to confirm this.

There were some limitations in the present study that could have affected the results. One was that with the resources available, it was not possible to separate all small pieces of vegetables mixed with rice or sauces from the rest of the food waste. To avoid sauces being mixed with other plate waste, plates could have been collected directly from pupils in the canteens, although this could have introduced bias by altering the food wastage behavior of the pupils. However, the level of separation achieved was deemed to be sufficiently accurate to allow the proportions of different plate waste components to be investigated. Another limitation was the lack of carbon footprint data, as specific values for each food item were not always available. To overcome this, carbon footprint values for food items from similar food groups were used, while also considering the origin of the food item (e.g., Sweden vs. South Europe) to achieve as accurate results as possible. A further limitation was that the carbon footprint did not include carbon emissions from distribution, storage, cooking, or cooling. Moreover, the carbon emission factors applied in the present study were based on life cycle assessment results, which should always be treated as approximate instead of precise values.

We investigated plate waste from only two elementary schools for children aged 6–9 years in Uppsala Municipality, Sweden. The composition of plate waste was consistent between the two canteens investigated and no difference in the quantity of plate waste was detected, suggesting that the results may be generalizable to similar canteens in Sweden and even school canteens outside Sweden with similar meal schemes, although more studies with larger sample size are needed to confirm the findings. Recognizing the small sample size of the present study, it involved plate waste analysis from two schools with approximately 307 daily guests observed over eight days, totaling approximately 4880 portions served, while prior studies varied in sample size from 23 schools with 46,988 portions (Silvennoinen et al., 2015) to as few as two schools with 3600 portions (Engström and Carlsson-Kanyama, 2004) and three schools with 755 portions served (Martins et al., 2016). More studies are also needed to determine whether the results are similar for canteens serving older school children, and to investigate possible differences between different socio-economic areas in addition to investigating their serving waste. Perhaps most importantly, future research should also focus on identifying tailored measures that reduce plate waste while also improving school children's food and nutrient intake, as very little is known at present about the degree to which food waste reduction measures influence the nutrition of school children.

5. Conclusions

Plate waste from the two Swedish elementary schools analyzed in this study was found to be nutritious and could meet previously identified gaps in the dietary intake of school children. The carbon footprint of the plate waste was lower than previously estimated, and the increasing trend for serving plant-based school meals may lead to further decreases. The carbon footprint could also be decreased through tailored food waste prevention measures targeting animal-based food waste. However, such prevention measures alone would not markedly reduce the overall amount of food waste or the nutrient loss embedded in the waste. Therefore, to meet food waste reduction goals while retaining valuable nutrients within the food system and using them as intended, i.e. to nourish school children, it is important to prioritize food waste reduction measures that result in adequate dietary intake of school children.

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CRediT authorship contribution statement

Niina Sundin: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Runa Halvarsson:** Writing – review & editing, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Silvia Scherhaufer:** Writing – review & editing. **Felicitas Schneider:** Writing – review & editing. **Mattias Eriksson:** Writing – review & editing, Funding acquisition.

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.

Data availability

Data will be made available on request.

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Appendix

Table A.1
School meal menu during the 10-day observation period in spring 2023.

Date	Weekday	Menu options
10 April	Mon	n/a (public holiday)
11 April	Tue	Pasta ratatouille
		Red lasagna with cottage cheese
12 April	Wed	Red curry with quorn/pork/chicken and basmati rice
13 April	Thu	Broccoli au gratin and cooked potatoes
		Fish au gratin seasoned with taco spice and cooked potatoes
14 April	Fri	Creamy cauliflower and coconut stew with bulgur
		Yakiniku chicken, vegetables, and noodles
17 April	Mon	Pasta with cheese and broccoli/ham/turkey
18 April	Tue	Root vegetable stir-fry with oven-baked beetroot
		Chicken and root vegetable stir-fry with curry sauce
19 April	Wed	Vegetable patties with lime sauce and cooked potatoes
		Fish au gratin seasoned Thai-style and cooked potatoes
20 April	Thu	Soup*
21 April	Fri	Kitchen's choice** including one vegetarian option

* No food waste was collected and analyzed, due to the liquid form of the food served.
** Contained beef.

Table A.2
Food waste components and their weight per canteen and collection day.

Collection date	Food category	Canteen A (kg)	Canteen B (kg)
11 April	Rice with red curry sauce, pieces of vegetables	5.68	5.6
	Chicken	0.42	0.6
	Quorn	0.1	
	Pasta	0.32	
	Mixed vegetables	0.52	0.22
	Olives	0.26	0.22
	Chickpeas	0.18	0.08
	Friarelli bell pepper	0.09	
	Feta cheese	0.02	
	Bread	0.18	0.08
	Other	0.04	0.04
	Total	*7.63*	*6.78*
	*Loss**	*0.11*	*0.04*
12 April	Lasagna (vegetarian)	5.98	8.5
	Chicken	0.14	
	Pasta	0.38	
	Mixed vegetables	0.56	0.48
	Olives	0.14	0.34
	Chickpeas		0.12
	Friarelli bell pepper	0.02	
	Orange peel	1.04	
	Pancake	0.16	
	Bread	0.86	0.08
	Other	0.16	0
	Total	*9.58*	*9.52*
	*Loss**	*0*	*0.08*
13 April	Fish, pieces	0.74	0.4
	Boiled potatoes	3.26	3.42
	Fish stew and potato, mushy (inseparable)		2.54
	Fish stew and rice, mushy (inseparable)	2.14	
	Burger (beef)	0.04	
	Sausage (pork)		0.08
	Lasagna (vegetarian)	0.54	
	Mixed vegetables	1.04	0.64
	Olives		0.2
	Chickpeas		0.1
	Carrots	0.22	
	Lemon, including peel	0.86	1.66
	Apple, including peel and core		0.36
	Egg	0.16	
	Pancake	0.08	
	Bread	0.2	0.42
	Other	0.18	0.08
	Total	*9.46*	*9.9*
	*Loss**	*0*	*-0.02*
14 April	Noodles	4.7	4.92
	Chicken	0.28	0.42
	Meatball**	0.08	
	Mixed vegetables	1.2	0.98
	Olives	0.08	0.06
	Carrots	0.24	
	Lemon	0.4	
	Orange	0.82	
	Apple core		0.04
	Egg	0.02	
	Bread	0.08	0.12
	Other	0.08	0
	Total	*7.98*	*6.54*
	*Loss**	*0.02*	*-0.02*
17 April	Pasta and sauce	5.74	7.18
	Ham	0.92	0.82
	Hamburger**		0.02
	Mixed vegetables	0.58	0.48
	Olives		0.12
	Carrots	0.22	
	Chickpeas	0.04	
	Butter beans		0.04
	Lemon, including peel	0.04	
	Apple, including peel and core		0.1
	Feta cheese	0.08	
	Egg	0.08	
	Bread	0.18	0.02
	Other	0.1	0.14
	Total	*7.76*	*8.92*

(*continued on next page*)

Table A.2 (*continued*)

Collection date	Food category	Canteen A (kg)	Canteen B (kg)
	*Loss**	*-0.02*	*0*
18 April	Stir-fry (potato, curry sauce, some vegetables)	4.14	6.06
	Chicken	0.5	0.5
	Meatballs**	0.04	
	Ham	0.22	
	Vegetarian meat substitute	0.02	
	Mixed vegetables	0.54	0.88
	Olives	0.18	
	Carrots	0.3	
	Chickpeas	0.08	
	Apple core		0.1
	Egg	0.16	
	Eggshell	0.08	
	Bread	0.2	0.3
	Other	0.06	0.02
	Total	*9.52*	*8.28*
	*Loss**	*0.12*	*-0.02*
19 April	Fish gratin	1.8	2.26
	Boiled potatoes	4.6	3.62
	Chicken	0.04	
	Meatballs**		0.16
	Vegetable patties	0.34	0.08
	Mixed vegetables	1.06	0.58
	Olives	0.08	
	Carrots	0.36	
	Butter beans		0.04
	Apple core		0.1
	Egg	0.04	
	Pancake	0.14	
	Bread	0.3	0.34
	Other	0.12	0.06
	Total	*10.42*	*7.74*
	*Loss**	*0.1*	*-0.04*
21 April	Spaghetti and sauce	4.96	4.82
	Bolognese**	1.08	1.02
	Sausage		0.1
	Mixed vegetables	0.16	0.12
	Olives	0.12	
	Friarelli bell pepper		0.18
	Apple core		0.04
	Cottage cheese	0.02	
	Egg	0.02	
	Bread	0.14	0.18
	Other	0.08	0.08
	Total	*6.58*	*6.54*
	*Loss**	*0*	*0.04*

* Loss: Difference between the mass of total food waste and mass of the total of aggregated food categories.
** Food category that contained beef.

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Food waste and overeating are widespread, while many remain food insecure. This thesis assessed overeating and food consumption as food waste reduction measure in Sweden. Using life cycle assessments, surveys, and nutritional calculations, the sustainability impacts of these measures were assessed. The results suggested the necessity of limiting food overconsumption not only from a health but also from an environmental perspective, whereas redirecting edible food waste to people did not only preserve the environment but also valuable nutrients, accruing potential health benefits.

Niina Sundin received her postgraduate education at the Department of Energy and Technology, Swedish University of Agricultural Sciences, Uppsala. She holds a Master of Science degree in Nutrition Science from Karolinska Institutet, Stockholm.

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