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Balancing people, planet, and profit in urban food waste management

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ABSTRACT

Food waste is a complex problem and critical challenge for the sustainable development of circular economies, with interconnected social, environmental, and economic impacts. Supporting the identification of strategies that best minimise these impacts on people, planet and profit, this paper explores the dynamic impacts of food waste management options on the triple bottom lines of sustainable development in urban circular economies. We present a system dynamics model of the urban agri-food supply chain. This model simulates the fluxes of food and food waste throughout the supply chain, as well as their impacts on economy (i.e., costs and benefits for each sector and the broader economy), society (i.e., food insecurity) and environment (i.e., water, energy, and carbon footprints). Using Bristol city in the United Kingdom as a case-study, we evaluate the impacts of seven food waste management options (i.e., reduction, redistribution, animal feed, anaerobic digestion, composting, incineration, and landfilling). The results show that food waste reduction in consumer sectors (i.e., households and hospitality and food services) and redistribution in supply sectors (i.e., primary production and manufacture) offer the greatest benefits for the environment, society, and economy. For the retail sector, both reduction and redistribution options are highly favourable. Although these options can potentially have some adverse economic effects on the supply side due to a reduction in demand, their considerably high benefits make them high-reward, low-risk options. We thus conclude that food waste reduction and redistribution are the only options with a clear triple-win for people, planet and profit. This paper makes a significant contribution by introducing a robust quantitative model and a novel triple bottom line framework for sustainable food waste management in urban circular economies.

1. Introduction

Food waste is a trillion-dollar global problem with substantial consequences for environment, society, and economy, which are known as the 'triple bottom line' of sustainable development (Bhattacharya et al., 2022; FAO, 2014). Every year, 14 % of harvested world's food is lost before reaching the supermarket shelves (FAO, 2019) and another 17 % is wasted in retail and consumer sectors (UNEP, 2021). The food that is produced and then wasted in this fashion accounts for 8–10 % of global greenhouse gas (GHG) emissions (UN, 2022). It is estimated that in addition to the USD 400 billion economic costs of food loss and USD 1 trillion of food waste, the global food wastage has an additional hidden cost of USD 700 billion for the environment and a further USD 900 billion for society (FAO, 2014, 2019). Meanwhile, the number of people suffering from hunger and lack of a healthy diet worldwide has risen to 828 million and 3.1 billion, respectively (FAO; IFAD; UNICEF; WFP; WHO, 2022). This – together with the waste of natural resources – makes food waste not 'just' an economic but a major ethical problem.

Given the enormous costs, reducing food waste and its associated economic, social, and environmental impacts is a priority for national governments and international organisations. Target 12.3 of the United Nations Sustainable Development Goals (SDGs) aims to halve food waste at the retail and consumer levels and to reduce food losses along agri-food supply chains by 2030 (UNEP, 2021). In Europe, under its Circular Economy Action Plan, the European Commission has also proposed legally binding food waste reduction targets of 10 % in manufacture and 30 % jointly at retail and consumer sectors by 2030 vs. 2020 food waste levels (European Commission, 2020, 2023). In the UK, the Courtauld Commitment 2030 is a voluntary agreement that targets to reduce 50 % of post-farm-gate food waste by 2030 (against the 2007 baseline) and 50 % of GHG emissions of the consumed food by 2030 (against a 2015 baseline), as well as to source 50 % of fresh

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food from areas with sustainable water management (WRAP, 2022a).

References to the 'reduction' or 'prevention' of food waste in such contexts are often generic and include food waste reduction at source, redistribution of surplus to people via charitable or commercial routes, and the diversion of surplus to animal feed (WRAP, 2020a). Moreover, circular economy (CE), as an increasingly popular approach among scholars, policymakers, and practitioners, endorses the food waste hierarchy framework and calls for the adoption of recycling and recovery options such as anaerobic digestion (AD), composting, and incineration as well. Each of these options has unique implications for the environment, society, and economy and it is assumed that the food waste hierarchy reflects a ranking of these options according to their lowest negative impact. However, as we further demonstrate below (see Section 2), the full impacts of different food waste management options across the triple-bottom lines have not yet been studied within the context of a dynamic food system. The variety of the possible circularity options means that food waste prevention, management, and valorisation in a CE thus still require a comprehensive and rigorous assessment of the socio-economic and environmental sustainability of each option (De Menna et al., 2018).

Addressing this need, the current paper aims to explore the dynamic impacts of food waste management options on sustainability's triple bottom lines in urban CEs. It does so by building a system dynamics model of the socio-economic impacts of food waste based on Parsa et al.'s (2023) environmental impact model. The combination of both modelling results can provide a comprehensive and detailed understanding of the dynamic impacts of urban food waste management options on the people, planet, and profit bottom lines of sustainable development. Hence, the key questions that this research seeks to answer are: a) what are the impacts of each food waste management option on different agents across agri-food supply chain, both individually and collectively? b) what are the most environmentally, socially, and economically sustainable food waste management options for urban CEs? and c) is a triple win for people, planet and profit achievable in case of food waste management in urban CEs? To address these questions, this study follows the following objectives:

i) to compare the financial costs and benefits of changes in food waste management options for each sector and the whole economy (Section 4.1);
ii) to explore the impacts of surplus redistribution on society (Section 4.2);
iii) to discuss the potential trade-offs and knock-on effects of food waste management options on different agents (Section 4.3);
iv) and, to provide a triple bottom line framework for guiding sustainable food waste policies and practices in urban CEs (Section 4.4).

We also reflect on the theoretical and practical contributions of answering the three overarching questions (Section 4.5), and on the study's limitations and future research directions (Section 4.6) before summarizing and concluding in Section 5.

2. Literature review

The concept of triple bottom line first emerged in 1990s to redefine corporate success by assessing the business implications for people, planet and profit bottom lines of sustainability (Loviscek, 2020; Nogueira et al., 2023). Since then, this concept has been widely adopted by sustainability scholars and practitioners as a conceptual framework and assessment approach that accounts not only for a business case for development but also for social equity and environmental sustainability as a holistic three-dimensional system of goals (Nogueira et al., 2023; Rogers and Hudson, 2011).

Regarding the critical impacts of food waste on the environmental, social (including ethical), and economic bottom lines, providing a triple bottom line framework for food waste management has been subject of numerous qualitative and quantitative analyses. Bhattacharya et al. (2022), for instance, conducted a qualitative literature review to identify specific interventions for food waste reduction at consumer-retailer, consumer-food businesses, and consumer-household interfaces that can achieve the triple bottom line wins. While achievable, the study argues that balancing environmental and social bottom lines with the economic dimension cannot always be realised due to conflicting perspectives and priorities among the different stakeholders (Bhattacharya et al., 2022).

Although the environmental benefits of reducing food waste are well evidenced in the literature (e.g., De Jong et al., 2023; Eaton et al., 2022; FAO, 2019; Parsa et al., 2023), depending on impacts on different agents, there is no consensus among scholars on socio-economic benefits of food waste reduction. Modelling the impacts of reducing urban food waste on the macro-economy, Black et al. (2023), for instance, conclude that food waste reduction would equally decrease the economic activity in food sectors and cause 'significant risks' to income of producers, suppliers and waste processors, and their employees. On the other hand, while acknowledging the potential 'negative economic impacts' on agri-food sectors, De Jong et al. (2023) show that reducing food waste improves efficiency in the supply chain, positively affects other economic sectors, and benefits households by increasing financial savings and food affordability. Similarly, Hanson and Mitchell (2017) analysed the costs and benefits of food waste reduction for different sectors and conclude that food waste reduction can lead to a triple-win for the economy, society, and environment.

The impacts of wider food waste management options on the triple bottom lines of sustainable development are studied predominantly through cost-benefit analysis and life cycle assessment methods. Using cost-benefit models to compare the economic favourability of anaerobic digestion (AD), biofuels production, incineration, and landfilling in the US, for example, Badgett and Milbrandt (2021) conclude that profitability of the options depends on local market variables, such as gate fees, bioenergy market prices and the treatment facility size; hence, there is no single most-profitable option. In the case of household food waste in the UK, Slorach et al. (2019) undertook life cycle assessment and life cycle costing methods to assess the environmental and economic costs of AD, in-vessel composting, incineration, and landfilling options. The study finds that the AD and incineration are the most sustainable options, respectively, while acknowledging that food waste prevention results in far greater environmental and economic savings (Slorach et al., 2019). Albizzati et al. (2021) provide a more comprehensive sustainability assessment of food waste management options at the EU level and the findings of their societal life cycle costing research reiterate the usefulness of the food waste hierarchy framework.

Such cost-benefit analyses and life cycle assessment studies provide valuable insights on the environmental, economic, and occasionally social impacts of food waste management in CEs. However, the static approach of these methods is a critical limitation to explore the existing feedback loops and dynamic interactions within such a complex system (Zhai et al., 2022). Given this limitation, system dynamics is regarded as a rigorous approach which enables modelling the feedback loops and interactive impacts of the food (waste) system and analysing its behaviour over time (Parsa et al., 2023). Moreover, the available studies usually focus on one or two bottom lines (e.g., Ahamed et al., 2016; Badgett and Milbrandt, 2021; Slorach et al., 2019); food waste from one or few agri-food sectors (e.g., De Menna et al., 2019; Slorach et al., 2019); and one or few management options (e.g., Alsaleh and Aleisa, 2022; Black et al., 2023; De Jong et al., 2023). This highlights the need for a comprehensive exploration of the environmental, social, and economic impacts of most common management options in CEs for food waste flows from different agri-food sectors. Hence, this study uses system dynamics modelling in pursuit of a comprehensive triple bottom line framework for food waste management in urban CEs.

3. Method and materials

This study uses system dynamics modelling (SDM) to simulate the socio-economic cost and benefit dynamics of food waste in urban CEs. The current model extends an extant food waste environmental impacts model (Parsa et al., 2023), and explores the social and economic impacts of different food waste management options in the case of Bristol city in the UK for a duration of 12 years (2018–2030). The following sections shed light on the initial and extended system dynamics model (Section 3.1) and the economic and social impacts of food waste (Sub-sections 3.1.1 and 3.1.2), as well as describing the case study area and specifying simulation scenarios (Section 3.2).

3.1. System dynamics modelling

System dynamics is *"a rigorous modelling method that enables to build formal computer simulations of complex systems and use them to design more effective policies and organisations"* (Sterman, 2000, p. vii). Modelling the dynamic interactions between a system's elements and existing feedback loops leads to a better understanding of its behaviour. In this study, we use SDM as the main method to simulate the socio-economic dynamics within the agri-food supply chain in order to explore the costs and benefits of different food waste management options for the agri-food sectors, both individually and collectively. Through a group model building process, Parsa et al. (2023) developed a dynamics model of agri-food supply chain to analyse the environmental impacts of food waste management in urban CEs. This study expands this model by adding the social and economic dynamics to it.

The initial model adopted an integrated CE-Nexus approach (Parsa et al., 2021) to explore the urban food waste impacts on food, energy, water, and climate (FEWC) nexus. Being applied to the case of Bristol city in the UK, the model simulated the energy, water, and carbon footprints of food system throughout the supply chain (i.e., primary production, manufacture, retail, Hospitality and Food Services (HaFS), and household) and compared the preferability of different food waste management options. Using a cradle-to-grave approach, the model provided a quantitative analysis of best food waste management practices and policies and an optimised version of the food waste hierarchy to guide rigorous environmental policies in urban CEs (for full details of the modelling process and results, see Parsa et al., 2023).

Here, to explore the costs and benefits dynamics, we expand the life cycle approach of the initial model by including socio-economic dimensions of food (waste) in the model (Fig. 1). The here presented version of the model, hence, enables cost and benefit analysis of different food waste management options in a dynamic urban CEs and an assessment of their impact on the economy, society, and environment. As the environmental impacts are discussed in detail in Parsa et al. (2023), this paper is dedicated to socio-economic aspects. In continuation to the previous work, the expanded model studies the socio-economic dynamics of food waste in the case of Bristol City in the UK. For economic impacts, we explore the dynamics of intermediate consumption, total turnover, waste collection and treatment costs, and approximate Gross Value Added (GVA) as the key indicators in each sector (Section 3.1.1). The impact of surplus redistribution on food insecurity is the primary social indicator investigated in this study (Section 3.1.2).

This version of the model (i.e., excluding environmental impacts sectors) has 464 variables, including 22 Stocks, 56 Flows, and 386 Converters. A complete list of equations, assumptions and data sources is provided in Supplementary Materials.

3.1.1. Economic impacts

Regarding the economic impacts on the primary production, manufacture, retail, and HaFS sectors, we explore the cost of changes in different food waste management options on each sector's intermediate consumption (i.e., total purchases of goods, materials, and services).

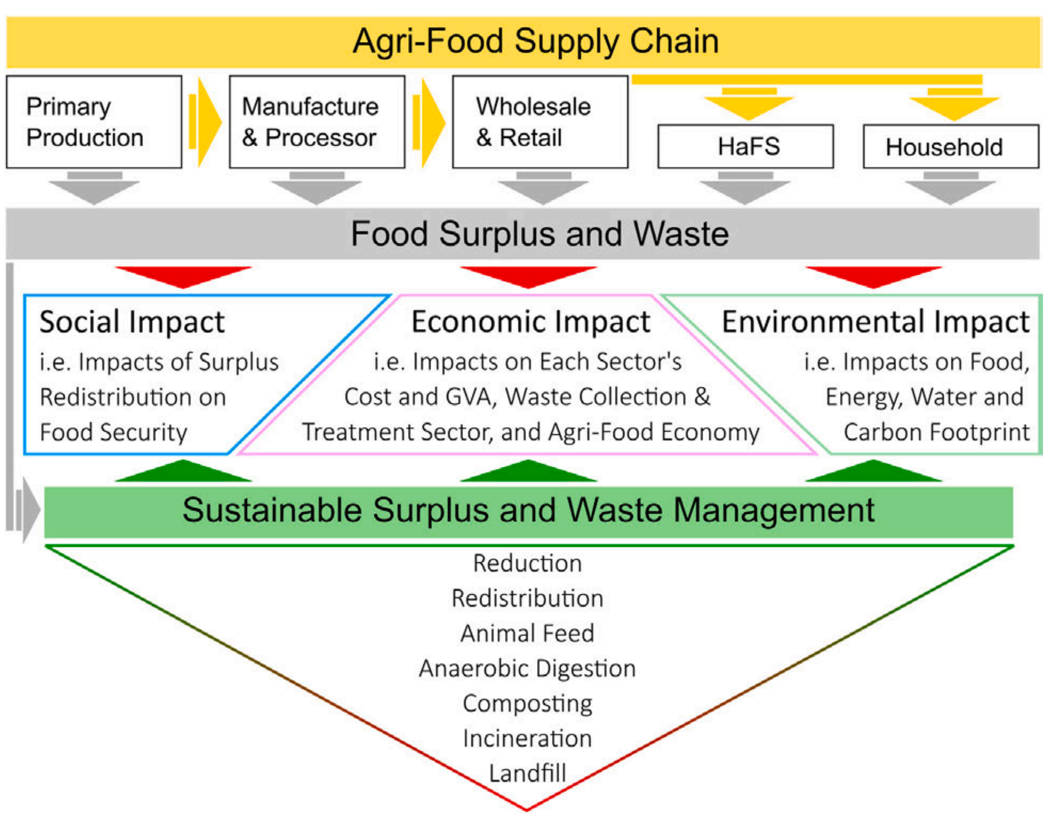

Fig. 1. System boundary of social, economic, and environmental impacts of urban food waste (arrows denote the flow of food and food waste; red and green triangles denote potential negative and positive impacts).

Table 1
Overview of simulation scenarios and key underlying assumptions.

Scenario	Description [a]	Parameter Change [b]	Key Assumptions [c]
S0	baseline – no changes in initial rate of each food waste management option	default parameter values	initial Bristol population: 463,400 annual population growth rate: 0.6 % initial HaFS food
S1	food waste reduction – including five sub-scenarios: $S1_{HH}$, $S1_{H}$, $S1_{R}$, $S1_{M}$, $S1_{PP}$	household ($S1_{HH}$): reduction +2.8 %; commercial sectors ($S1_{H}$, $S1_{R}$, $S1_{M}$, $S1_{PP}$): reduction +3.6 %	demand: 73,900 t annual HaFS growth rate: 1.5 % initial household food waste: 18.4 % of
S2	increased redistribution – including four sub-scenarios: $S2_{H}$, $S2_{R}$, $S2_{M}$, $S2_{PP}$	commercial sectors ($S2_{H}$, $S2_{R}$, $S2_{M}$, $S2_{PP}$): redistribution +3.6 %	purchased food (~46,000 t) rate of change in household alternative scenarios:
S3	increased animal feed – including four sub-scenarios: $S3_{HH}$, $S3_{R}$, $S3_{M}$, $S3_{PP}$	household ($S3_{HH}$): animal feed +2.8 %; commercial sectors ($S3_{R}$, $S3_{M}$, $S3_{PP}$): animal feed +3.6 %	2.8 % of initial household food waste (~1290 t per year) initial HaFS food
S4	increased AD – including five sub-scenarios: $S4_{HH}$, $S4_{H}$, $S4_{R}$, $S4_{M}$, $S4_{PP}$	household ($S4_{HH}$): AD +2.8 %; commercial sectors ($S4_{H}$, $S4_{R}$, $S4_{M}$, $S4_{PP}$): AD +3.6 %	waste: 16 % of purchased food (~11,650 t) rate of change in HaFS alternative
S5	increased composting – including five sub-scenarios: $S5_{HH}$, $S5_{H}$, $S5_{R}$, $S5_{M}$, $S5_{PP}$	household ($S5_{HH}$): compost +2.8 %; commercial sectors ($S5_{H}$, $S5_{R}$, $S5_{M}$, $S5_{PP}$): compost +3.6 %	scenarios: 3.6 % of initial HaFS food waste (~420 t per year) initial retail food
S6	increased incineration – including five sub-scenarios: $S6_{HH}$, $S6_{H}$, $S6_{R}$, $S6_{M}$, $S6_{PP}$	household ($S6_{HH}$): incineration +2.8 %; commercial sectors ($S6_{H}$, $S6_{R}$, $S6_{M}$, $S6_{PP}$): incineration +3.6 %	waste: 0.7 % of acquired food (~2300 t) rate of change in retail alternative
S7	increased landfill – including five sub-scenarios: $S7_{HH}$, $S7_{H}$, $S7_{R}$, $S7_{M}$, $S7_{PP}$	household ($S7_{HH}$): landfill +2.8 %; commercial sectors ($S7_{H}$, $S7_{R}$, $S7_{M}$, $S7_{PP}$): landfill +3.6 %	scenarios: 3.6 % of initial retail food waste (~83 t per year) initial manufacture
R0	baseline – no changes in initial rate of each food waste management option	default parameter values	food waste: 2.6 % of acquired food (~9000 t) rate of change in manufacture
R1	increased redistribution of surplus in HaFS sector	HaFS redistribution +3.6 %	alternative scenarios: 3.6 % of initial manufacture food waste (~323 t per
R2	increased redistribution of surplus in retail sector	retail redistribution +3.6 %	year) initial primary production food waste: 3.2 % of
R3	increased redistribution of surplus in manufacture sector	manufacture redistribution +3.6 %	produced food (~12,000 t) rate of change in primary production
R4	increased redistribution of surplus in primary production sector	primary production redistribution +3.6 %	alternative scenarios: 3.6 % of initial primary production food waste (~433 t
R5	combined – sum R1-P4	R1+ R2 + R3 + R4	per year)

[a] Indices of sub-scenarios in S1-S7 refer to agri-food supply chain sectors: HH = household, H = hospitality and food service (HaFS), R = retail, M = manufacture, PP = primary production.
[b] Annual linear change in parameter value, applied over 12-year simulation.
[c] The full list of assumptions and data sources are presented in Supplementary Materials.

Each sector's average intermediate cost per tonne of food (waste) is estimated based on data from the Office of National Statistics (ONS, 2022a). We use the mean of deflated values during 2016–2020 to minimise the effect of food market fluctuations in the data set. Any changes in food waste management practices of the sectors can affect the intermediate consumption through the food cost and/or waste collection and transfer costs (including gate fees).

At the household level, we scrutinise the economic impacts of changes in food waste management options on household expenditure on food, energy and water costs associated with the food preparation and the food waste collection and disposal costs. We also explore the impacts of such changes on local (and national) government costs, including waste collection and gate fees (Boulding and Barker, 2021), as well as the cost of food waste reduction initiatives (e.g., surplus redistribution and food waste reduction campaigns).

In addition to assessing the costs and benefits of different food waste management options for each sector, it is crucial to explore their implications on other economic agents and the whole agri-food economy. Our model simulates these dynamic impacts by analysing the total output of the food and food waste treatment sectors and their intermediate costs. To analyse the costs and benefits for food waste treatment agents (e.g., AD and incineration plants), we compare the operational and capital costs with the generated revenues from each treatment option. The impact on the whole economy is then estimated by the sum of the approximate Gross Value Added (GVA) of the sectors, which is equal to the output at basic prices less the intermediate consumption (ONS, 2018).

Reducing food waste in each commercial sector can proportionally reduce the 'intermediate consumption' while reductions at household level decrease households' food purchasing cost and its associated energy, water, and waste collection and disposal costs. Despite the benefits, food waste reduction is not free of cost. Hanson and Mitchell (2017) provide a benefit-cost ratio framework which is adopted in our model to estimate the cost and benefit of reducing food waste in each sector. Although Hanson and Mitchell (2017) acknowledge that the benefit-cost ratios decrease as "low-hanging fruits" run out, they do not provide a spectrum for the estimated ratios. Following the law of diminishing returns, we assume that the cost of further reduction interventions increases exponentially as the amount of food waste reduces linearly.

3.1.2. Social impacts

There is no consensus on social indicators of CE strategies, but consumer and occupational health and safety, poverty, and food security are recognised as highly relevant indicators for evaluating CE performance in a society (Padilla-Rivera et al., 2021). Since a rigorous health and safety analysis of food systems requires a highly granular approach to food products and further disaggregation of the model, we leave the analysis of this important indicator for future studies. To explore the social impacts of food waste management, we focus here on poverty and food security indicators.

According to the Declaration of World Food Security, *"Food security exists when all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life"* (World Food Summit, 1996). We use the national data from the 'Food and You 2' survey to estimate the number of 'food insecure' population in Bristol. This includes populations with 'low food security' (i.e., those reported of 'reduced quality, variety, or desirability of diet, [but] little or no indication of reduced food intake') and 'very low food security' (i.e., those reported of 'multiple indications of disrupted patterns and reduced food intake') (Armstrong et al., 2023a).

The impact of food surplus redistribution on food security and a 'win-win narrative' is a source of controversy among scholars and activists (e.g., Papargyropoulou et al., 2022). Taking a conservative approach, we assume that redistribution of commercial food surplus can effectively mitigate the 'very low' food security rate (hereafter 'severe food insecurity' which describes the population who reported hunger/ reduced food intake) while having no impact on the 'low' food secure population (i.e., those who reported reduced food quality, variety, or desirability of

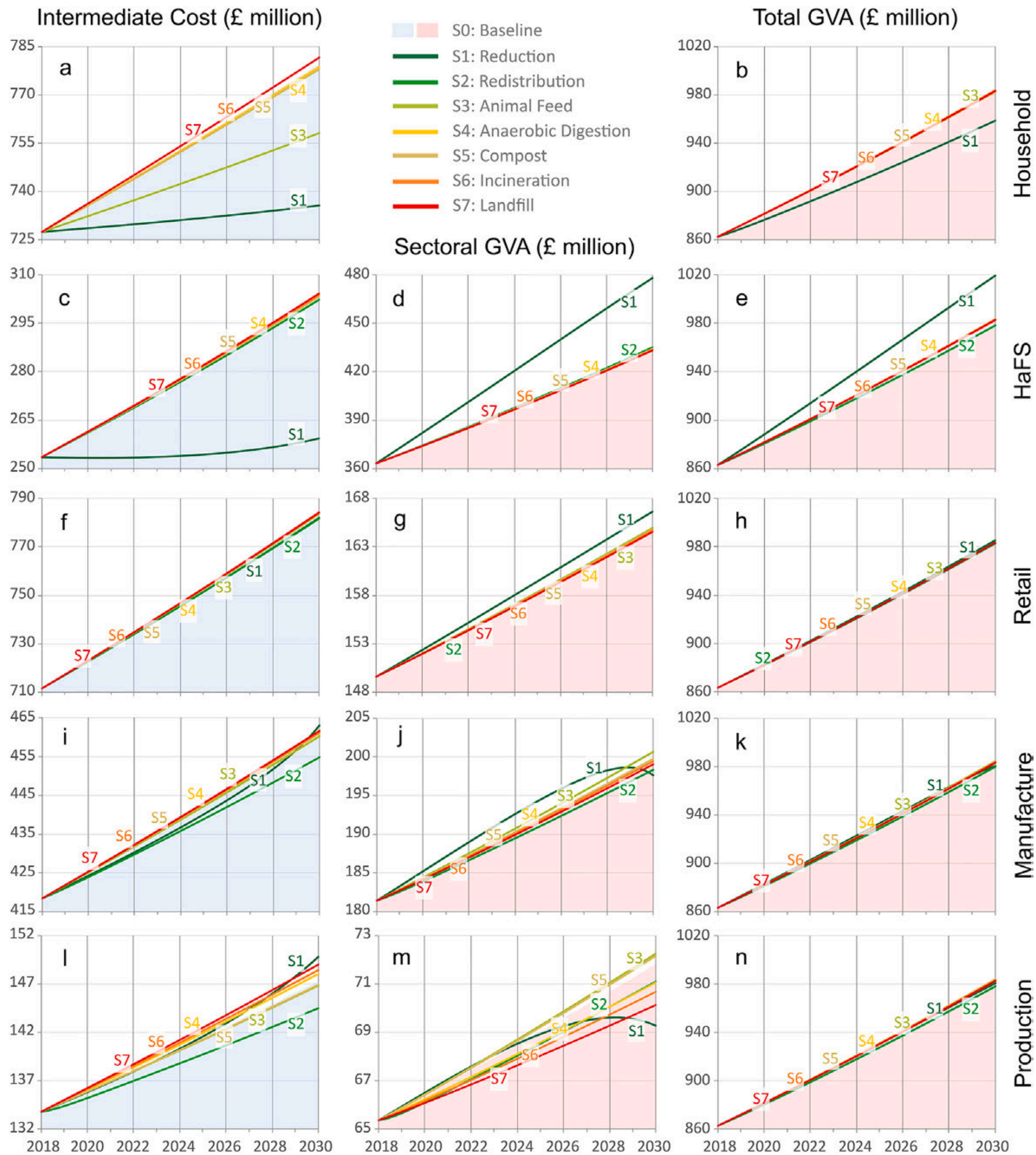

Fig. 2. Impact of food surplus and waste management options on intermediate cost (first column), Gross Value Added (GVA) (second column), and total GVA (third column) of agri-food sectors. Blue shading shows the area of cost reduction (positive impact), and red shading shows the area of GVA reduction (negative impact).

diet). Hence, rather than focusing on the food insecurity indicator (as the sum of low and very low food secure populations), our model explores the impacts of surplus redistribution on severe food insecurity.

It is important to notice that in redistribution scenarios, 'who pays' (i.e., food sector, government, and/or food charities) differs from 'who benefits' (i.e., households). Hence, while the cost of redistribution is estimated based on data from Fareshare (2023) and WRAP (2022b), the household benefit is assumed to be equal to the reduced food purchase cost.

3.2. Case study and scenarios

To be consistent with Parsa et al. (2023), this model is also applied to the case of Bristol city. Bristol is the largest city in the South West region of England with a population of 463,000 in 2018 which is expected to grow to 533,000 by 2043 (BCC, 2020; ONS, 2020). The city is recognised as a pioneering environmentally friendly city in the UK and Europe which aims to become carbon neutral by 2030 (Bristol One City, 2020). With the highest level of productivity per capita among the major cities and an employment rate of 78.1 % (compared to 74.8 % Great Britain average), Bristol has one of the most vibrant and successful economies in

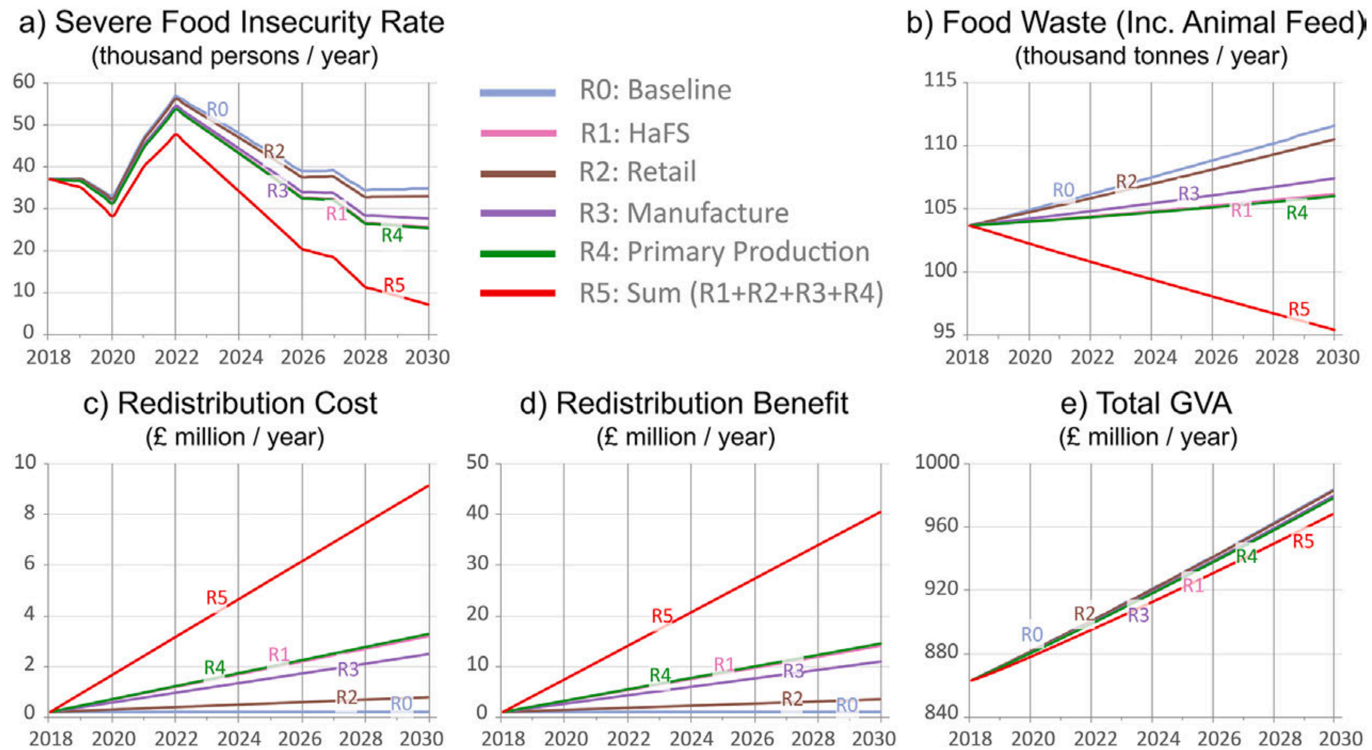

Fig. 3. Impacts of food surplus redistribution on number of Bristol residents with severe food insecurity (a), urban food waste (b), redistribution cost (c), redistribution benefits (d), and total gross value added (GVA) of agri-food supply chain (e).

the UK (BCC, 2022). Nevertheless, 15 % of Bristol population live in the 10 % most deprived areas in England and 17.9 % of children under 16 live in low-income families (compared to 19.1 % national average) (BCC, 2022).

We simulate the current socio-economic impacts of Bristol food waste management options (Baseline Scenario) with alternative scenarios during a 12-year simulation period (2018–2030). The alternative scenarios assume an equal amount of food surplus and waste at each sector is reduced, redistributed, fed to animals, composted, sent to AD, incinerated, or landfilled. We specify these scenarios based on the Courtauld 2030 target (WRAP, 2022a). To meet this target, household and commercial food waste should be reduced by an annual rate of 2.8 % and 3.6 %, respectively, against the 2018 amounts (Parsa et al., 2023). Hence, we compare the changes in critical variables for a 2.8 % annual linear increase in food waste reduction, animal feed, anaerobic digestion (AD), composting, incineration, and landfill for household and a 3.6 % linear change in the same management options (plus redistribution) for HaFS, retail, manufacture, and primary production sectors. For all scenarios, the urban population (thus, household food demand) and HaFS sector are assumed to grow by an annual rate of 0.6 % and 1.5 %, respectively (Parsa et al., 2023). These growth rates are considered reasonable over the time-limited simulation period given recent data (ONS, 2020, 2022b; Parry et al., 2020). While the full list of equations, assumptions and data points are documented in Supplementary Materials, Table 1 summarises the scenarios and key underlying assumptions of this study.

3.3. Model validation

Validation of a system dynamics model is a complicated and difficult problem, both philosophically and technically. While the philosophical challenge is rooted in the controversial enduring debate on verifying the 'truth' of a scientific statement, the technical difficulty comes from the limitation of established formal tests to verify that the model structure and behaviour is 'close enough' to the real system (Barlas, 1996). Since historical time series data on food waste and its environmental, social and economic impacts at local scale do not exist for Bristol, Appendix 3 in Supplementary Materials elaborates why and to what extend the findings of the model is trustworthy. A reflection on boundary adequacy and structure assessment, an extreme conditions test, and a sensitivity analysis are presented to showcase the robustness and usefulness of the model in a formal validation process (see Supplementary Materials, Appendix 3).

4. Results and discussion

This section presents the modelling results for economic (Section 4.1) and social (Section 4.2) impacts of food waste management in the Bristol City. As outlined in Section 3.2, all of the scenarios assume annual growth rates of 0.6 % and 1.5 % for urban population and HaFS sector, respectively. After discussing the socio-economic impacts of different food waste management options (Section 4.3), we combine them with the environmental impacts of corresponding options (based on Parsa et al., 2023) to deliver a triple bottom line framework for guiding environmentally, socially, and economically sustainable food waste management policies in urban CEs (Section 4.4). Finally, the contributions and limitations of this study are discussed in Sections 4.5 and 4.6, respectively.

4.1. Economic impacts of food waste management

The following scenarios compare the baseline scenario (i.e., no changes in food waste management), with a 2.8 % annual change in each food waste management option for households and a 3.6 % change for commercial agri-food sectors. We choose these rates since they are linked to relevant existing policy guidance. As indicated above, to meet the Courtauld 2030 commitment, it is estimated that household and commercial food waste should be reduced by an annual rate of 2.8 % and 3.6 %, respectively, compared to the 2018 amounts (Parsa et al., 2023).

At the **household** level, the 0.6 % annual population growth rate

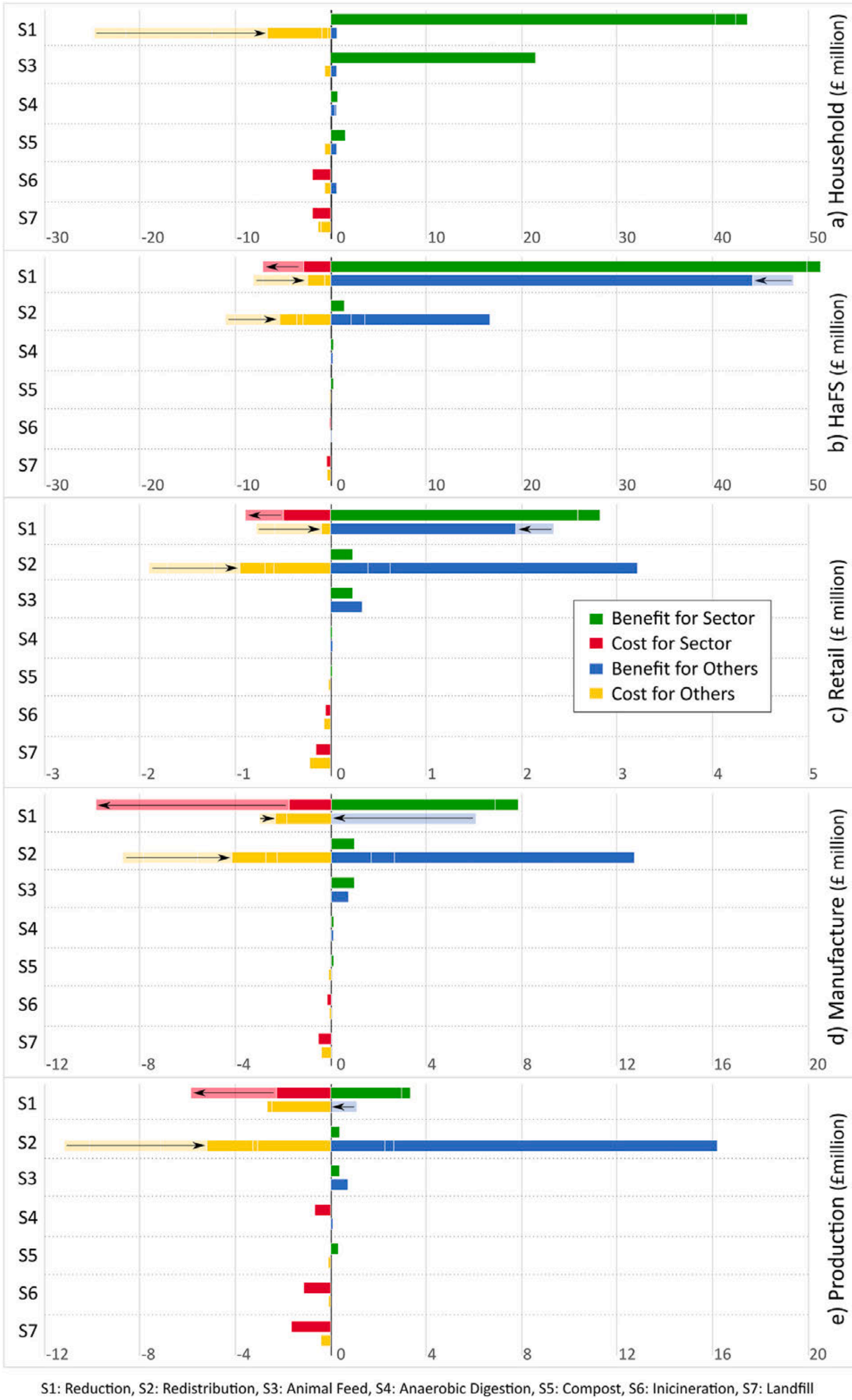

Fig. 4. Costs and benefits of food waste management across the agri-food sectors, analysed separately for the contributing sectors (red and green) and the broader economy (yellow and blue). Red shades with arrows illustrate increasing costs as food waste amounts reduce. Blue shades with arrows illustrate the corresponding change in the GVA of the sectors. Yellow shades with arrows illustrate the reduced impact due to export/ import and re-spending dynamics. HaFS = hospitality and food service.

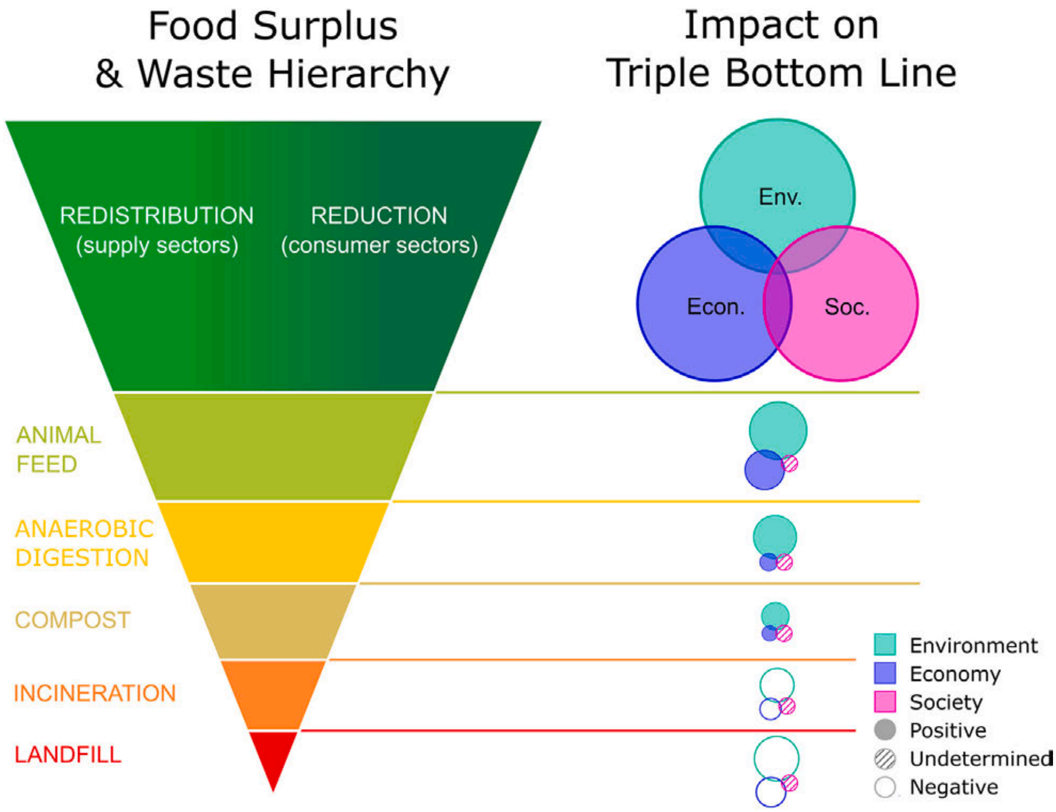

Fig. 5. Impact of food waste management options on environment, economy, and society. Circle sizes are normalized to the maximum value in each of the three categories, using data from Parsa et al. (2023) and Table A2.1 in Supplementary Material.

means that Bristol household food demand is expected to increase by >7 % by 2030, as a consequence of which Bristol households would buy 18,700,000 t more food, costing £52,200,000 more compared to 2018 demand (Fig. 2a: S0). Given that, the 2.8 % annual reduction scenario (Fig. 2a: S1) cuts the total household cost by up to 6 % (or £44,000,000) by the end of the simulation. This includes £40,400,000 less for food purchases, £1,900,000 less for energy, £300,000 less for water, and £1,300,000 less for waste collection and disposal costs. On the other hand, the reduction in demand affects the supply proportionately and shrinks the agri-food economy by £24,900,000 in GVA and £15,400,000 in intermediate consumption of the supply sectors compared to the baseline scenario (Fig. 2b: S1).

Feeding the leftover food to pets (Fig. 2a: S3) is the next best cost-mitigating option as it saves households up to £21,400,000, which would otherwise be spent on pet feed purchases. Other scenarios have a minor impact on household costs as they only affect waste collection and treatment costs. Home composting (Fig. 2a: S5) can replace up to £1,600,000 worth of compost at retail price, reducing household costs by up to 0.2 %. If the food waste is not fed to pets or composted, households have to pay the service cost of £34 and £214 per tonne of food waste and residual waste, respectively, for collection and disposal costs (WRAP, 2021). Hence, the AD scenario (Fig. 2a: S4) reduces the service cost by £800,000 while increasing incineration and landfill (Fig. 2a: S6 and S7) raises the costs by £2,000,000 by the end of the simulation.

The impact of non-reduction scenarios on GVA is minimal (Fig. 2b: S3-S7). Since the model does not account for the GVA of the pet feed sector, the scenario's impact on agri-food GVA is almost identical to the baseline scenario (Fig. 2b: S3). Nevertheless, if the impact on the feed market were included, the total GVA would illustrate a similar behaviour to the reduction scenario. The rest of the food waste management scenarios affect the total GVA by less than £1000,000. AD and incineration scenarios (Fig. 2b: S4 and S6) increase the GVA by £500,000 and £700,000, while home-composting and landfill (Fig. 2b: S5 and S7) decrease it by £700,000 and £300,000, respectively.

While the food demand of **HaFS** is expected to increase by 14,600 t in 2030, a 3.6 % annual food waste reduction (Fig. 2c: S1) is the best option for the sector to minimise the cost. As the food waste reduces, the cost-benefit ratio grows exponentially from 0.059:1 to 0.144:1. This means it would be almost 2.5 times more costly to reduce food waste in 2030 than in 2018. The curved reduction line (Fig. 2c: S1) illustrates this behaviour. Nevertheless, the reduction scenario can save up to £44,300,000 by the end of the simulation, of which £1,500,000 saving comes from the need for less food waste collection and lower treatment costs. The reduction in intermediate consumption boosts not only the GVA of HaFS but also the total GVA of the agri-food economy significantly. Although the reduction in HaFS demand shrinks the supply and waste management sectors and reduces their GVA by £8,500,000, the growth in HaFS GVA is much higher and is sufficient to compensate for the loss in other sectors and to increase the total GVA by £35,800,000.

The impacts of other food waste management scenarios on HaFS intermediate cost are substantially smaller than the reduction scenario. While households are the primary beneficiaries of food surplus redistribution, the redistribution scenario (Fig. 2c: S2) still saves up to £1,500,000 for HaFS due to the reduced food waste management cost. With a commercial waste collection cost of £150 per tonne, the minor differences between the following scenarios (Fig. 2c: S4 to S7) are due to variable transfer costs (including gate fees and landfill tax) for each management option. As such, increasing AD and in-vessel composting (Fig. 2c: S4 and S5) with a transfer cost of £76 per tonne of food waste are relatively less costly options than incineration and landfill (Fig. 2c: S6 and S7) with transfer costs of £156 and £256, respectively.

Since redistribution reduces the intermediate cost of HaFS, the GVA of the sector increases equally by £1,500,000 (Fig. 2d: S2). However, its impact on total GVA is negative and higher (i.e., £7,000,000 by 2030) as the redistribution cuts household purchases and consequently downsizes the supply by up to 0.7 % (Fig. 2e: S2). AD, compost, incineration, and landfill with £251,000, −£17,000, £6000 and −£434,000 changes in total GVA, respectively, have a negligible effect on the economy (Fig. 2e).

Food surplus and waste management in **retail** (Fig. 2f) has a minimal effect on intermediate costs because the sector's waste generation rate is much lower than others (i.e., 0.7 % vs. 18.4 % in households and 16 % in HaFS). Given that, the 3.6 % annual food waste reduction (Fig. 2f: S1) can reduce around £1000 t of food waste and £1,900,000 intermediate cost by 2030. As food waste reduces, the cost-benefit ratio of reduction for retailers increases exponentially from 0.2:1 to 0.35:1 over the simulation period. Given that, redistributing the same amount, with no extra cost for the sector, cuts the intermediate cost of the sector by £500,000 more than the reduction (Fig. 2f: S2). This promising cost mitigation, however, results from shrinkage in retail turnover. In fact, the redistribution of retail surplus can shrink the GVA of the retail sector and the wider economy by £200,000 and £800,000, respectively (Fig. 2g and h: S2).

Sending the food waste to be used as livestock feed (Fig. 2f: S3) is a cost-free measure for the sector as it cuts the waste collection and transfer costs. Other measures (Scenarios S4 to S7) have similar impacts on retail intermediate cost, GVA and the whole economy to HaFS.

The difference between waste management scenarios is more visible in **manufacturing**, with a higher food waste generation rate (i.e., 2.6 %) than in the retail sector (Fig. 2i, j, and k). While all scenarios show similar trends to the retail sector, the most distinctive behaviour can be seen in the reduction scenario (Fig. 2i: S1), where the intermediate cost gradually increases over time and eventually becomes the costliest option. This is due to the exponential growth of the cost-benefit ratio from 0.26:1 in 2018 to 1.42:1 in 2030. This means meeting the Courtauld 2030 target, only through reduction, could gradually cost the manufacture sector more than any benefit it can gain from food waste reduction. Although such a scenario is unlikely to happen in a real-world setting (and even if it does, it will disrupt the supply and raise the food prices proportionally), the simulation model illustrates how such a hypothetical scenario decreases the GVA of the sector and the agri-food economy when the cost-benefit ratio exceeds 1:1 (Fig. 2j and k: S2).

Contrary to other sectors, food waste reduction in **primary production** does not even start as a low-cost measure (Fig. 2l: S1). The cost ratio for reducing food waste in the sector is estimated to be £0.77 for each £1 benefit, and it grows to 2:1 by the end of the simulation. This hypothetical scenario suggests that high reduction targets for the sector could impose substantial costs and drop its GVA dramatically (Fig. 2m and n: S1). Although the Courtauld Commitment 2030 does not set any reduction target for primary production, the reduction scenario shows the damaging impact of radical food waste reduction targets on primary production's costs and GVA.

Redistribution (Fig. 2l and m: S2), as discussed, shrinks demand and supply, leading to a smaller primary production sector with lower costs and GVA. Unlike other sectors, however, the GVA of the sector in the redistribution scenario (Fig. 2m: S2) is still higher than in costly incineration and landfill scenarios (Fig. 2m: S6 and S7). This places the latter options as the costliest and hence, least preferrable measures for the primary production.

4.2. Social impacts of food waste management

Based on Food and You 2 surveys, the percentage of the UK population (except Scotland) classified as 'very low' food secure increased from 7 % in Wave 1 (July to October 2020) to 12 % in Wave 6 (October 2022 to January 2023) (Armstrong et al., 2023b, 2023a, 2022b, 2022a, 2021a, 2021b). Considering the population growth as well as the correlation between food insecurity and inflation rate, the baseline scenario (Fig. 3a: R0) shows that Bristol population with severe food insecurity fluctuates between 37,100 and 32,800 before it peaks at 57,000 in 2022 and decreases gradually after that. It is worth noting that the peak in 2022 and the gradual decline afterwards is only an optimistic assumption for comparative modelling.

The following four scenarios (Fig. 3: R1 to R4) illustrate the impact, a 3.6 % annual increase in commercial sectors redistribution would have on population with severe food insecurity (Fig. 3a), on urban food waste (Fig. 3b), on redistribution cost to government (Fig. 3c), on redistribution benefit for households (Fig. 3d), and on total GVA (Fig. 3e). As all of these scenarios show similar behaviour, we only discuss the results of Scenario R5, which is the sum of HaFS, retail, manufacture, and primary production redistribution scenarios (i.e., R1 + R2 + R3 + R4).

Meeting the Courtauld 2030 target of halving food waste by redistribution of food surplus means that the number of Bristol's residents experiencing severe food insecurity would decrease by 80 % compared to the baseline scenario (Fig. 3a: R5 vs R0). Although this reduces up to 16,100 t of urban food waste (Fig. 3b), the sum scenario (R5) indicates that 7,000 people would still live with severe food insecurity (Fig. 3a: R5).

With an estimated cost of £590 per tonne of redistribution (based on Fareshare, 2021), such an initiative can cost up to £9,100,000 per year for the government (assuming the government funds the scheme to a charity like Fareshare) while benefiting the in-need households to cut their food purchase expenditure by up to £40,400,000 per year (Fig. 3c and d). This also indicates that any alternative programme which entails direct food purchase for food insecure households can cost the government at least four times more than surplus redistribution initiatives.

As discussed in the previous section, the modelling results suggest that food redistribution reduces demand and consequently shrinks the food supply and waste management sectors. Taking the estimated £7,600,000 added value of the redistribution into account, the negative impact of the sum scenario (R5) on the total GVA is estimated to be £15,100,000 by the end of the simulation (Fig. 3e).

4.3. Rethinking the socio-economic impacts

Compared to other measures, food waste reduction has the highest benefit for household, HaFS and retail sectors (Section 4.1). The cost-benefit ratio of food waste reduction, however, increases as we move from consumers towards the top of the agri-food supply chain. Although the median ratio for manufacture and primary production is below 1:1 in the beginning, the cost of reduction in these sectors surpasses its potential benefit when there is less food waste available. Hence, this diminishing return effect, eventually, makes food waste reduction at manufacture and primary production a high-cost and low-reward measure. While reduction becomes less and less cost-effective when moving up in the agri-food chain, redistribution becomes more and more beneficial to mitigate household food purchase costs. It is because the redistribution shortens the supply chain, and the inexpensive food in upstream supply sectors replaces the higher-priced food in the retail sector. The redistributed surplus benefits not only the households but also the participating sectors as it reduces their cost of food waste management.

Although the modelling results illustrate a robust case for the cost-effectiveness of food waste reduction in consumer sectors and surplus redistribution in supply sectors, these measures reduce the demand which can subsequently shrink the supply sectors. Such a potential negative impact on the agri-food economy is often flagged as a critical challenge for growing CEs (e.g., Black et al., 2023). Given that, it is essential to remember that the growth rate in urban food demand (due to population and HaFS growth) is significantly higher than any practical reduction rate (see Total GVA graphs in Fig. 2). For example, meeting the ambitious Courtauld 2030 target for household food waste can reduce the household food demand by 15,500 t. Despite that, the agri-food economy would still grow at a rate of £8,000,000 per year compared to £10,000,000 per year in the baseline scenario (Fig. 2b). It is obvious that this does not apply to a city with a net zero or negative population and/or HaFS growth rate. Overall, the simulation findings indicate that food waste prevention can cause a slowdown in GVA growth in a growing economy or a further contraction in a shrinking economy. However, this should not be translated that the prevention leads to a recession in the agri-food economy.

Moreover, the modelling results reported in section 4.1 assume the Bristol agri-food sector is a closed system. Such an assumption is usually inevitable for modelling the dynamics of a complex system such as the urban food system (Pruyt, 2013). In real-world open systems, however, reducing consumer demand in one urban area does not necessarily shrink the supply sectors. Food producers and manufacturers can manage redundant stocks by increasing exports and/or decreasing imports. Hence, food waste reduction or surplus redistribution is unlikely to affect the GVA of primary production and manufacturing sectors. Although a demand reduction can affect retail sales, it does not lead to an equivalent loss of revenue for the sector. A WRAP econometric study suggests that half of the household savings accrued through food waste reduction is spent on more expensive food (i.e., 'trade up') and the other half is either spent on other products/services or saved (Britton et al., 2014). Hence, it is more realistic to assume that a reduction in consumer demand in a city like Bristol would not affect the GVA of primary production and manufacturing sectors (i.e., due to the export and import dynamics) while causing only a 50 % loss to the GVA of wholesale and retail as consumers re-spent at least half of their savings in the sector.

Integrating these considerations with the modelling findings shows that food waste reduction in consumer (i.e., household and HaFS) and retail sectors has the highest profit for these sectors (Fig. 4a,b,c: S1; Table A2.1 in Supplementary Materials). The savings in these sectors come with a significantly smaller impact on the GVA of the food supply and waste management sectors. This confirms the findings of a recent European Commission study, which concludes that food waste reduction in the EU may cause negative economic impacts on agri-food sectors, but it creates positive effects in other sectors, which compensate for the losses on the one hand and increase food affordability and household savings on the other (De Jong et al., 2023). As such, our results suggest that there is no economic justification for an urban CE to prioritise the minor commercial gains over the food waste reduction benefits in this trade-off. The market value of food in the household, HaFS, and retail sectors is much higher, and the reduction cost is much lower compared to the upstream supply chain. These conditions mean that food waste reduction in these sectors is a high-reward and low-cost opportunity. Among these sectors, food waste reduction at HaFS has the highest benefit for the sector and the wider economy because of its significantly higher food prices.

On the other hand, while reduction gets more costly for upstream supply sectors (i.e., primary production and manufacture) (Fig. 4d,e; Table A2.1 in Supplementary Materials), redistribution becomes the most profitable option, both for them and for the broader economy (Fig. 4d,e: S2). It is also the best option for the retail sector if impacts in the broader economy are prioritised over the sectoral gains. The redistribution option provides a triple-win ground for these sectors to meet the Courtauld 2030 target while reducing their food waste collection and treatment costs and contributing to feeding the food insecure households. As discussed in Section 4.2, however, providing food for all in-need households cannot be achieved even with the total of simulated scenarios. This highlights the need for a more comprehensive plan to tackle food insecurity by maximising the surplus redistribution and combining it with other effective schemes (i.e., those tackling poverty and its underlying issues) which guarantee physical and economic access to sufficient, safe, and nutritious food for all people, at all times.

Compared to the benefits of reduction of food waste in consumer and retail sectors and redistribution in all supply sectors, the impact of other food waste management options on each sector and the whole agri-food economy ranges from minor benefits to moderate costs (Fig. 4: S3-S7). Feeding the food leftover to pets at the household level can be regarded as an exception with promising cost savings for households and a potentially small negative impact on the broader economy (Fig. 4a: S3). It is important to emphasise that although, for example, converting food waste into livestock feed has a positive return for the engaged sectors and broader economy, the benefits are much smaller than the best options for each sector. Hence, placing it in an unweighted food waste hierarchy as the next preferable option after reduction and redistribution can be erroneous and misleading (Parsa et al., 2023). The same applies to other treatment options where AD and compost options can be generally classified as low-reward, and incineration and landfill as moderate-cost measures.

4.4. Towards a triple bottom line framework

These findings align with the environmental impacts of food waste on the food, energy, water and climate (FEWC) nexus in urban CEs as reported in Parsa et al. (2023). They illustrate that the impacts of food waste management options vary from one sector to another (e.g., primary production vs. household food waste), and from one nexus element to another (e.g., water vs. carbon footprint). Nonetheless, the paper highlights that reduction within consumer sectors and redistribution at supply sectors are the most environmentally sustainable options while other options have substantially lower preferability and higher potential of trade-off between FEWC footprints (Parsa et al., 2023). Integrating the findings of both studies provides a triple bottom line framework for food waste management in urban CEs (Fig. 5).

Since reduction and redistribution at consumer and supply sectors, respectively, have the highest benefit for the environment, economy and society, the circle sizes representing each bottom line illustrate approximate relative weight of other management options to these options (Fig. 5). Given that, the figure clearly shows how substantially the benefits of reduction and redistribution for people, planet and profit outperforms the environmental and economic gains of animal feed, AD and compost, as the CE's most promising options. Although the social impact of food surplus and waste in this study is limited only to food (in) security, even including new indicators for social pillar of sustainability (e.g., equity, health, well-being, etc.) is unlikely to change the size of social impact circles in Fig. 5 dramatically. Hence, it can be concluded that a triple-win for people, planet, and profit in food waste management in urban CEs is achievable if food waste prevention (i.e., reduction in consumer sectors and redistribution in supply sectors) is highly prioritised, and the next recycling options (i.e., animal feed, AD and composting) are only regarded as the last resort for treating unavoidable food waste.

It is important to emphasise that this simplified illustration of the framework (Fig. 5) is only aimed to represent the approximate normalised scale of different food waste management impacts on triple bottom line, and obviously does not depict all the detailed trade-offs reported in both studies. This abstract holistic approach to the agri-food system is both useful and essential for making sustainable urban policies. Lack of a holistic systems approach can lead to misinterpretation of the data. For example, a 'reductionist' interpretation of the modelling data presented in Section 4.1 could lead to the conclusion that food waste reduction (at least at household level) is detrimental to the agri-food economy. As discussed in above section, however, looking at the bigger picture beyond annual agri-food GVA data, it appears that food waste reduction helps the household to save money and buy more quality food (i.e., trade up) while cutting the local government costs (e.g., gate fees). It even does not necessarily shrink the GVA of upstream supply sectors, thanks to the export and import mechanisms. As interviews with food businesses (Hanson and Mitchell, 2017) and food waste treatment plants (Parsa et al., 2023) explicitly indicate, these sectors are not only concerned about consumers' food waste, but also want to actively contribute (financially and non-financially) towards its reduction.

4.5. Theoretical and practical contributions

Transition to a sustainable and circular food waste management system that accounts for the environmental, social and economic sustainability has been gaining traction in recent years (Bhattacharya et al., 2022; UNEP, 2021). As discussed in Section 2, numerous recent studies adopted life cycle assessment and cost-benefit analysis approaches to shed light on the implications of different food waste management options for all or some aspects of the people, planet and profit bottom lines of sustainable development (e.g., Ahamed et al., 2016; Alsaleh and Aleisa, 2022; Badgett and Milbrandt, 2021; Bhattacharya et al., 2022; Kim et al., 2011; Slorach et al., 2019). Contrary to these studies, we use a system dynamics model to provide a comprehensive and detail understanding of the food waste management impacts on the triple bottom line framework.

To the best of our knowledge, this is the first comprehensive application of system dynamics modelling for exploring the environmental, social, and economic impacts of urban food waste throughout the agri-food supply chain. The system dynamics approach of this study enables the provision of novel insights about the preferability and profitability of different food waste management options beyond the extant literature. Shifting the priority from the reduction to redistribution option while moving from consumer to supply sectors, for instance, is a nuanced finding of simulating the supply chain interactions and feedback loops in the dynamics model. Exploring such dynamic behaviours in the agri-food system is a valuable methodological advantage of adopting the system dynamics modelling.

Moreover, the dynamics model in Parsa et al. (2023) and this study simulates the impacts of agri-food sectors' food waste on FEWC system (i.e., environmental impact), food insecurity (i.e., social impact), and costs and benefits for each sector and the whole economy (e.g., economic impact). Such analysis of the impacts of seven food waste management options in five sectors on the three dimensions of sustainable development presents a comprehensive picture of the food waste impacts in urban CEs. Hence, the wide scope and high detail of the analysis in this study constitutes another substantial contribution to the body of knowledge in the emerging CE literature.

Finally, this study not only presents a critical account of the status quo, but also proposes a data-driven alternative understanding of food waste impacts, which is manifested in the form of the simplified triple bottom line framework (Fig. 5). The nuanced and clear recommendations of the study provide a useful guidance for transitioning to more 'sustainable and circular' food waste management policies, while the replicable and reproducible dynamics model could be used by other scholars and policymakers for simulating bespoke policy scenarios.

4.6. Limitations and routes for future research

The purpose of the dynamics modelling in this study was to explore the impacts of food waste in urban CEs. The study's exploratory modelling approach (Desjardins et al., 2020) means that the model intended neither to explain the root causes of food waste generation in agri-food sectors, nor to predict the future state of the system. While this study concluded that food waste reduction and redistribution can lead to a triple-win for people, planet and profit, further explanatory modelling can help to understand the systemic barriers to the application of such preventive policies. Moreover, the UK data shows that although food waste level had fallen sharply in 2020 during the first Covid-19 lockdown, it since has had an upward trend towards pre-pandemic levels despite the emerging cost of living crisis (WRAP, 2023, 2020b). Due to the exploratory approach of this study, our modelling findings have not reported the impacts of such significant real-world events on the food (waste) system. Hence, further systemic studies are needed to investigate the challenges of and solutions for sustainable food waste prevention strategies.

The environmental model from Parsa et al. (2023) and the complementary socio-economic model in this study explore the most important environmental and socio-economic impacts of food waste in the food system of urban CEs. With >600 variables, the final model is an example of a big and extensive model in the system dynamics literature. Yet, although the detailed approach of the model facilitated the triple bottom line analysis of the food waste impacts, the included indicators and variables can by no means depict an exhaustive picture of the complex environmental, social, and economic impacts of the urban food system. The here presented open-access model can be extended in the future to analyse the impacts of food waste management on further environmental (e.g., wastewater and eutrophication), social (e.g., consumer and occupational health and safety) and economic (e.g., employment and livelihood) indicators.

Moreover, qualitative modelling at this scale is data intensive. Although this study tried to extract the data from most reliable sources in the literature, the data availability and compatibility was a critical challenge for the modelling process. As historical and time series data at local scale often does not exist, the parameters' values of the model were mostly estimated based on different available national datasets and scientific literature, which often lack compatibility and consistency. This challenge restricts the ability of modellers to develop precise predictive models or to test their models against historical data. Hence, we recommend that key government and non-government organisations, such as Department for Environment, Food and Rural Affairs (DEFRA) and Waste and Resources Action Programme (WRAP) in the UK, provide more granular and detailed datasets on food impacts to facilitate creation as well as validation of future models.

Finally, this study used a systems approach to showcase the possibility of a triple-win opportunity for food waste management in urban CEs. Regarding the importance of waste hierarchy framework in the CE literature, future research can apply similar systemic tools and techniques to examine the generalisability of this study's findings to other resources/ sectors beyond the food and food waste system. A systemic knowledge of the environmental and socio-economic impacts of different waste management options for different resources enriches the CE literature and lays the foundation for more sustainable policies.

5. Conclusion

Guiding best food waste policies requires a comprehensive understanding of food waste impacts on the environment, society, and the economy. Completing the triple bottom line approach, this study builds on Parsa et al.'s (2023) environmental dynamics model to also include the exploration of specific social and economic impacts of food waste management options in urban circular economies. The resulting detailed system dynamics model was used to compare the costs and benefits of different food waste management options (i.e., reduction, redistribution, animal feed, AD, compost, incineration, and landfill) for individual agri-food sectors (i.e., primary production, manufacture, retail, HaFS, household) and the broader socio-economic system.

Our findings show that at the consumer (i.e., HaFS and household) and retail sectors, food waste reduction has the highest benefit for these sectors. Although this reduces the demand and consequently affects the supply sectors, we argued why it is unlikely that a practical food waste reduction target causes any tangible impact on the supply sectors. Overall, considering the export and import tools in the production and manufacturing sectors, the effect of consumer 'trade up' behaviour on the retail sector, and the high benefits of food waste reduction in participating sectors, the reduction option is a high-reward and low-risk option for the whole economy.

As further advances in reducing food waste become increasingly costly and economically unviable for production and manufacturing, redistribution becomes the most beneficial option for these sectors and society. Redistribution of surplus food in these two sectors, as well as in the retail sector, reduces their food waste collection and treatment costs on the one hand, and the rate of urban residents living with severe food insecurity on the other. The modelling results, however, suggest that the redistribution measure alone is unlikely to eliminate the problem of people living with severe food insecurity in an urban CE like Bristol.

Overall, reduction in consumer sectors and redistribution in supply sectors have the highest socio-economic benefits for urban CEs. As a central point within the agri-food supply chain, the retail sector can uniquely benefit from both increased reduction or redistribution of food waste. Other food waste management options have significantly lower impacts, ranging from minor positive (e.g., animal feed and AD) to moderate negative (e.g., landfill and incineration) effects. These findings, interestingly, align with the environmental impacts of food waste management options, as reported by Parsa et al. (2023). Integrating these findings, this study provides a modelling-based data-driven triple bottom line framework for food waste management which highlights that while food waste reduction and redistribution present a clear triple-win for people, planet, and profit, other circularity options can only be considered last resorts for treating unavoidable waste. The distinctive findings of this study help demystify common misconceptions of food waste impacts in urban CEs.

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CRediT authorship contribution statement

Ali Parsa: Conceptualization, Methodology, Formal analysis, Investigation, Resources, Writing – original draft, Visualization. **Marco Van De Wiel:** Conceptualization, Methodology, Validation, Writing – review & editing, Supervision. **Ulrich Schmutz:** Conceptualization, Methodology, Writing – review & editing, Supervision. **Ivan Taylor:** Methodology, Validation, Writing – review & editing. **Jana Fried:** Methodology, Writing – review & editing, Supervision.

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.

Supplementary data

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