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Research article

Challenging the food waste hierarchy

Ali Parsa[a,*], Marco Van De Wiel[a,b], Ulrich Schmutz[a], Jana Fried[a], Daniel Black[c,d], Ian Roderick[e]

[a] Centre for Agroecology, Water and Resilience, Coventry University, UK
[b] College of Agriculture and Environmental Sciences, UNISA, South Africa
[c] Daniel Black + Associates | db+a, Bristol, UK
[d] Population Health Sciences, University of Bristol, UK
[e] The Schumacher Institute, Bristol, UK

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ABSTRACT

Food waste is a multi-faceted and complex problem for urban circular economies with far-reaching environmental impacts. Effectively addressing this problem requires a comprehensive understanding of the food waste impacts on food, energy, water, and climate (FEWC) systems. Despite complex dynamics in the FEWC nexus, the most popular guidance for food waste management is the food waste hierarchy framework – which fails to account for ensuing impacts on all nexus elements.

Aiming to optimise the framework, we adopt a participatory approach to develop the first comprehensive and replicable system dynamics model of the FEWC footprints of urban food waste throughout the agri-food supply chain. The quantitative model compares different food waste management options, and relevant policies in Bristol, UK (2018–2030).

Unlike the guidance of the traditional waste hierarchy framework, our findings show that the preferability of each option can vary for each sector within the supply chain and for each FEWC element. Our results show that increasing food surplus redistribution in the supply sectors and reducing food waste in consumer sectors are the most preferable approaches to reduce the environmental impacts of food. Feeding food leftover to pets at household level also has a promising impact. Other options involve trade-offs between energy and carbon footprints, while having minimal impact on water footprint.

We conclude that the traditional food waste hierarchy is too simplified to provide reliable guidance for environmentally sustainable food waste management and policy. Instead, we present an improved food waste hierarchy framework that accounts for the scale of preferability of each option for different sectors and different FEWC nexus elements. This novel framework thus provides more nuanced and more robust understanding of food waste impacts on the FEWC nexus in urban circular economies, thereby enabling the development of policy and management options that are optimised for environmental sustainability.

1. Introduction

About one billion tonnes (or 17%) of the total food produced for human consumption globally is wasted in households, food service, and food retail (UNEP, 2021). It is estimated that almost 690 million people around the world (9% of global population) experienced hunger, and 2 billion people (more than one quarter of the population) were affected by moderate or severe food insecurity in 2019 (UN, 2021). Minimising food waste not only paves the path to the Zero Hunger Goal of UN Sustainable Development Goals, but also substantially reduces the pressure on natural resources, given that agriculture and food supply chain accounts for 70% of global freshwater abstractions and 30% of global energy consumption, respectively (FAO, 2014). It would also help to reduce the current 8–10% of global greenhouse gas (GHG) emissions associated with food loss and waste, which if it was a country, it would have the third biggest carbon footprint in the world (UNEP, 2021).

Urban areas accommodate more than half of the world population, and account for 60–80% of global energy and more than 75% of natural resources consumption (UNEP, 2011). Moreover, urban populations are predicted to consume 80% of global food in 2050 (EMF, 2019). This

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* Corresponding author.
E-mail address: parsaa@coventry.ac.uk (A. Parsa).

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places cities at the epicentre of food waste generation and management. The huge environmental, social, and economic impacts of food waste in urban areas highlights the urgent need for transitioning to a circular economy (CE). In contrast to the 'take, make, dispose' model of the traditional linear economy, CE envisages an economic system based on 'designing out waste and pollution', 'keeping products and materials in use', and 'regenerating natural systems' principles (EMF, 2017). CE is an increasinlgy popular paradigm that emphasises a systemic shift in production, distribution and consumption processes guided by the waste hierarchy framework (i.e., reducing, alternatively reusing, recycling and recovering materials, respectively) (Kirchherr et al., 2017).

Although the increasing adoption of CE strategies in green cities is promising, some scholars raise the concern that closing the materials loop does not necessarily lead to environmental sustainability (Del Borghi et al., 2020; Laso et al., 2018; Parsa et al., 2021; Slorach et al., 2020). The critique of CE is that it fails to account for the wider impacts of food waste on other sectors such as water, energy, and climate, thereby raising the risk of burden shifting from one sector or resource to another (Del Borghi et al., 2020; Lehmann, 2018; Parsa et al., 2021). Some argue that addressing this blind spot may require integrating the CE with a 'nexus' approach: an emerging systemic approach to analyse the complex interlinkages between resources (e.g. food, energy, water) to identify potential inter-sectoral synergies and trade-offs for resources and waste minimisation (Lehmann, 2018; Zhang et al., 2018).

Admitting to the critical interdependence between both concepts, this study adopts an integrated CE-Nexus approach (Parsa et al., 2021) to explore the most preferable food waste management options and policies in the context of urban CE. According to the waste hierarchy framework of the CE, the most preferable food waste management options respectively are reduction, and then redistribution, feeding to animals, anaerobic digestion (AD), composting, incineration, and finally landfilling (Fig. 1). By modelling the dynamics of urban food waste throughout the supply chain (i.e., production, manufacture, wholesale and retail, hospitality and food service (HaFS), and household), we explore if and how the food waste hierarchy framework can be optimised to sustainably manage the food waste problem while minimising its impacts across the whole food, energy, water, and climate (FEWC) nexus.

Although several studies have assessed the environmental impacts of food waste using life cycle thinking methods (e.g., Eriksson et al., 2015; Reutter et al., 2017; Slorach et al., 2020; Song et al., 2015; Tonini et al., 2018), adopting nexus thinking in urban CE settings may enable a more substantive shift in sustainability studies (Parsa et al., 2021; Slorach et al., 2020). Depending on the nexus elements and system boundaries in the studies, several authors have indicated that the CE's waste hierarchy provides a useful framework for food surplus and waste management (e.g., Eaton et al., 2022; Eriksson et al., 2015; Oldfield et al., 2016; Tonini et al., 2018). For instance, comparing the GHG emissions of food waste in Uppsala, Sweden, Eriksson et al. (2015) conclude that the waste hierarchy framework is a 'useful, but approximate' tool for prioritising the available options. In contrast, however, comparing the impacts of AD, in-vessel composting, incineration, and landfilling on the food, water, energy, and health nexus, Slorach et al. (2020) argue that in-vessel composting is the worst option for environmental sustainability, since in-vessel composting is a net consumer of grid electricity, and has the highest impact on the food, energy and health elements. Given that composting is preferred over incineration and landfilling in the food waste hierarchy, Slorach et al. (2020) emphasise that higher preference in the food waste hierarchy does not necessarily equate to greater environmental sustainability.

Moreover, most of the life cycle assessment (LCA) studies represent a static approach that does not reflect the feedback loops and dynamic interactions within the system over time (Zhai et al., 2022). In contrast, adopting a system dynamics approach in this study enables the modelling of these interactive impacts, which has the potential to lead to long-term changes in the system. Although system dynamics has been used by previous studies for modelling food systems (e.g., Strapasson et al., 2020), comparing food waste policies (e.g., Lee et al., 2018; Zhu et al., 2020), waste management in specific sectors (Tseng et al., 2019), or broader nexus contexts (e.g., Hussien et al., 2017; Valencia et al., 2022), no study has so far adopted system dynamics modelling (SDM) to explore the dynamics of food waste impacts on the FEWC nexus throughout the supply chain.

Given that the majority of the current literature on food waste is LCA-based which focuses only on one or two environmental impacts (e.g., carbon and water footprint), and one waste generator sector (Tonini et al., 2018), this study aims: (i) to model the dynamics of urban food waste and its impacts on the FEWC nexus throughout the agri-food supply chain (Section 2); (ii) to explore and compare the environmental impacts of food waste management options as well as relevant national and local policies on urban FEWC footprints (Section 3.2 and 3.3); and (iii) to analyse the usefulness of food waste hierarchy framework for urban CEs in light of the nexus approach (Section 3.4).

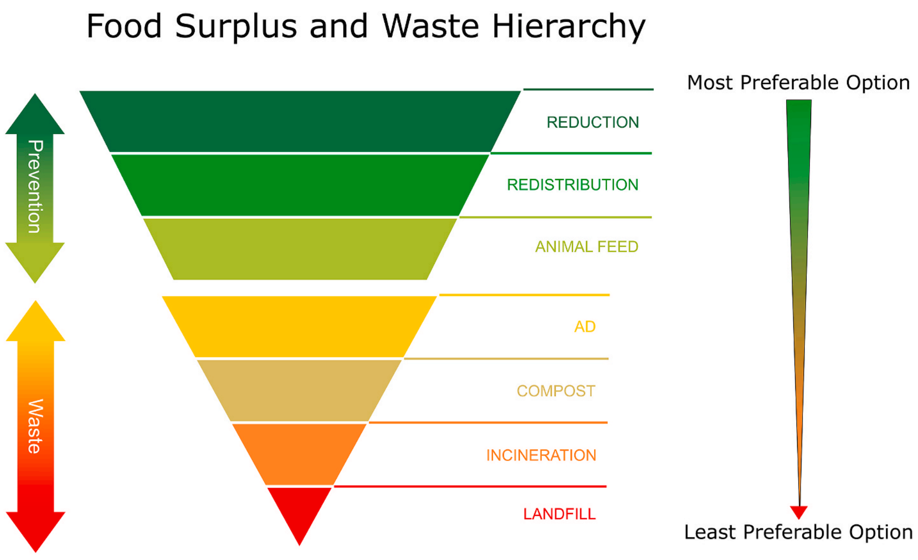

Fig. 1. Food surplus and waste hierarchy (WRAP, 2020a).

2. Methods and materials

This study uses SDM as the core method to simulate the dynamics of food waste and its impacts on the water, energy, and carbon footprints in the city of Bristol, UK during a period of 12 years (2018–2030). This timeframe is selected because most of the data used in the model is from 2018, and the end year of the relevant policies simulated by the model is 2030. Given the complexity and interdisciplinary nature of urban FEWC dynamics, enabling interactions between, and participation of, experts and stakeholders in the process of model building is of great importance. A group model building (GMB) approach can add to the robustness of the model and the usefulness of its output since this iterative, collective process allows to move beyond the narrower expertise of particular sectoral stakeholders or specific academic knowledge holders (Bérard, 2010). The following subsections introduce the case study area, the GMB process, and the SDM method adopted in this study in more detail.

2.1. Case study: Bristol city

Bristol is the largest city in the South West region of England, and one of 11 UK Core Cities, an alliance that aims to harness the full capabilities of urban areas in order to establish a more robust and equitable economy and society (Core Cities UK, n.d.). The population of the city is currently just over 466,000 and is projected to grow by 15% over the next quarter century to reach 533,000 b y 2043 (BCC, 2020). Bristol is known as a pioneering green city in the UK and Europe. It was the UK's first city to develop a climate strategy in 2004, to become the European Green Capital in 2015, and to declare a climate emergency in 2018. Based on the latter, the city is committed to become carbon neutral and climate resilient by 2030 (Bristol One City, 2020).

In 2006, Bristol became the first UK core city to separately collect household food waste while limiting residual waste capacity to increase food waste capture (Bristol Going for Gold, 2021). Bristol's main sewage and food waste treatment plant in Avonmouth, a port area outside the city, collected more than 14,000 tonnes of Bristol household food waste for AD treatment in 2019–20 (DEFRA, 2021). The city has recently been awarded Gold Sustainable Food City status in recognition of the positive work undertaken across its food system, which includes striving towards 'zero food waste' by embedding CE and food waste hierarchy principles into its food policies (Bristol Going for Gold, 2021).

2.2. System Dynamics Modelling (SDM)

As an interdisciplinary subfield of systems theory, 'system dynamics is a method to describe, model, simulate and analyse dynamically complex issues and/or systems in terms of the processes, information, organizational boundaries and strategies' (Pruyt, 2013). The method helps to study the dynamic behaviour of a system by exploring interactions between its variables and feedback loops. This is based on the fundamental assumption of system dynamics that the behaviour of a system is broadly shaped by its structure. The modelling and simulation method, hence, can lead to a better understanding of dynamic behaviour of complex real-world systems and eventually to improve their undesirable behaviours (Pruyt, 2013; Sterman, 2000).

This study uses Stella Architect (isee systems, 2019), a model building and simulation software, to develop a Causal Loop Diagram (CLD) and then, a stock-flow simulation model of food waste's FEWC impacts. Visualising the causal relationships between variables in a system, a CLD helps to communicate the positive and negative feedback loops in the system quickly and concisely (Richardson, 1986). Therefore, developing the CLD of the Bristol food waste impacts on water, energy and carbon footprint has been the first step in model development in this study.

Using stock and flow variables as the main building blocks of SDM, a simulation model can be developed based on the key variables and feedback loops identified in the CLD. A stock in SDM is a variable that accumulates and stores whatever flows into it (inflow), minus whatever flows out of it (outflow). The rate of inflows and outflows can be modified by auxiliary variables, parameters and constants, and causal links. Data and equations that define the relationship between these variables are sourced from the literature as well as the GMB process.

2.3. Group Model Building (GMB)

GMB, as a methodological framework which enables the participation of a diverse range of stakeholders in the various phases of model development, can serve SDM in various aspects. Benefits can occur in problem identification, aggregation of information and knowledge, recognition of expectations and for trust-building. As such, conceptualization and development of the model is not the sole outcome of GMB. In fact, the interactive process can further raise motivation and awareness among community decision-makers on one hand and build trust in modelling results and 'joint-ownership' of the model on the other hand (Hovmand, 2013; Rich et al., 2016). This, in turn, has the potential to lead to greater uptake of the model and its results outside a narrow academic context.

While there is no globally recognised methodological framework for GMB projects, various proposed frameworks emphasise the importance of structural elements including group structure and logistics as well as process aspects including problem articulation, dynamic hypothesis, simulation model formulation, model testing, and formulation of potential strategies and evaluations (Bérard, 2010; Sterman, 2000). Adopting this classification and modelling process with respect to available resources and limitations (e.g., Covid-19 restrictions), the main stages of this modelling process are summarised in the following flowchart (Fig. 2). A detailed description of the GMB stages is presented at Appendix 1 in Supplementary Materials.

2.4. Simulation scenarios

To explore the behaviour of each food waste management option, two sets of scenarios are specified. The first set of scenarios compares the current impacts of each food waste management option on the FEWC nexus (Baseline Scenario) with hypothetical scenarios in which an equal amount of urban surplus and waste is reduced, redistributed, fed to animals, composted, sent to AD, incinerated, or landfilled (Scenarios I1–I7, Table 1). The Baseline Scenario uses contemporary values derived from the literature, reflecting the recent (i.e., 2018) situation in Bristol. For the hypothetical scenarios, a 2% linear increase per year is assumed for each applicable option in each sector individually (i.e., household, HaFs, retail, manufacture, and primary production). This assumption is chosen because a 2% increase for 12 years (or 24% by the end of simulation time) in each of the simulated scenarios is possible both in theory and in practice for Bristol. Here, the 2% change denotes equal amounts of total food waste in that sector (as of 2018 values) which is proportionally reduced from other treatment options. The purpose of these scenarios is to explore how adjustments to individual management options affect the system's dynamics. Bristol's population and HaFS sector are therefore assumed to be steady (i.e., zero growth) in this set of scenarios (Table 1).

In the second set of scenarios, the impact of different policies on the FEWC nexus is simulated (Scenarios P1–P7, Table 1). These scenarios compare the environmental footprint of adopting national and local food waste reduction initiatives with a baseline case. For all the scenarios at this second stage, we assume annual growth rates of 0.6% for population (based on BCC, 2020) and 1.5% for HaFS sector (based on Parry et al., 2020). The baseline scenario assumes all other parameters, including the food waste generation, energy consumption, water abstraction, carbon emission fractional rates, are constant during the simulation time.

Scenarios P1 and P2 simulate the food waste reduction target of the Courtauld Commitment 2030. In line with the UN Sustainable

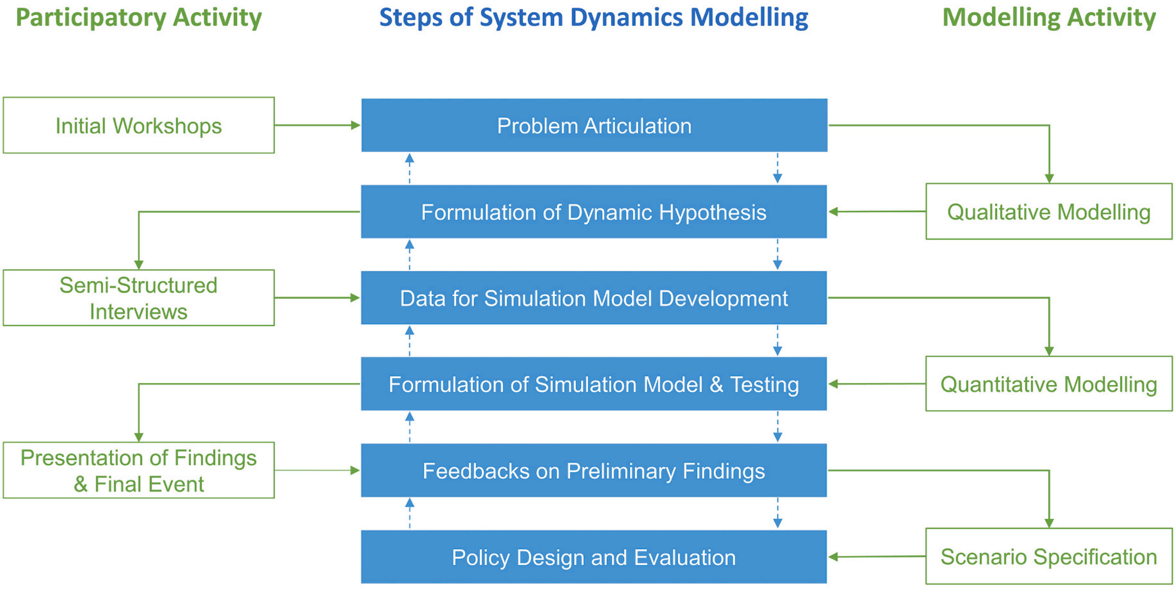

Fig. 2. Methodological framework for group model building (GMB). The green arrows indicate the temporal nature of the different steps, whereas blue dotted arrows highlight the nonetheless iterative nature of the GMB.

Development Goal 12.3, the Courtauld Commitment is a voluntary agreement aiming for a 50% per capita reduction in farm-to-fork food waste across the UK supply chain (i.e., excluding primary production) by 2030 vs the 2007 baseline (Wrap, 2022). The Courtauld Commitment contains two further target areas including reducing 50% of GHG emissions associated with food and drink consumption, and sourcing 50% of fresh food from areas with sustainable water management. Since this paper focuses specifically on food waste management impacts (and not systemic change in the food system), the latter targets are not considered herein. In order to meet the food waste reduction target, UK households need to reduce 2.8% of their food waste every year from 2018 to 2030 while the annual reduction rate for commercial food waste is around 3.6%. Since food waste reduction, surplus redistribution and animal feed are all considered as prevention measures, and hence uniformly recommended to meet the target, in scenario P1 (Courtauld Initial), we equally divide the given rates between the potential options. In scenario P2 (Courtauld Optimal), we assume annual 2% reduction and 0.8% animal feed for households, 2.5% reduction and 1.1% redistribution for HaFS, and 1.1% reduction, 1.8% redistribution, and 0.7% animal feed for retail and manufacture food waste.

In scenario P3 (Net Zero, 2050), the purpose is to simulate the FEWC impacts of decarbonising electricity according to the UK's net zero target by 2050 (BEIS, 2021a). Although Bristol has already set the plan to be a carbon neutral city by 2030, the reliance of its food and energy system on the UK's policy on one hand and lack of local data on the other hand are the main reasons for adopting the net zero by 2050 scenario. As such, the electricity emission factor is assumed to be declining from 0.234 kg CO_{2e}/kWh in 2018 to 0.052 kg CO_{2e}/kWh in 2030 (around 6.5% reduction per year) based on the UK consumption-based grid electricity emission factor (BEIS, 2021b).

Scenarios P4–P6 investigate the impact of local initiatives indicated in the Bristol One City Plan. Aiming to make Bristol a fair, healthy, and sustainable city, the One City Plan is a participatory attempt to set out a shared vision and goals of the city up to 2050 (Bristol One City, 2021). The plan outlines the route for Bristol to become carbon neutral and climate resilient by 2030 and a zero-waste city by 2050. Since local food growing and sustainable urban farming are key elements of the One City plan, scenario P4 (Urban Farming) assumes 12% of the total food consumed in Bristol is sourced from the city region by2030.[1]

In scenario P5 (AD increase) we assume a 3% per year increase in AD treatment of household food waste, which is compatible with the city's aim to reduce the amount of food waste into residual waste to 10% by2025.[2]

Moreover, as the city aims to cut household water consumption by 25% by 2045, in scenario P6 (Water Reduction), we assume a 1% per year reduction in household water use for cooking and dishwashing.

Finally, Scenario P7 combines all of Scenarios P2–P6 (including Courtauld Optimal, Net Zero, 2050; Urban Farming, AD Increase, and Water Reduction) to show the total impact of these policy measures on the urban food and food waste system.

3. Results and discussion

3.1. *Bristol food (waste) flow and its energy, water and carbon footprint*

Quantification of food (waste) and its energy, water, and carbon footprints is a critical preliminary step in understanding the complex dynamics of the FEWC nexus. Due to lack of specific data on Bristol food (waste) and its energy, water, and carbon footprint across the supply chain, we first provide a reference mode of the system, presenting the estimated contemporary energy, water, and carbon footprints of food and food waste flow in the city of Bristol (Fig. 3). Food waste quantification practices often tend to exclude the food waste in primary production sector (e.g., WRAP, 2020a). Here, we instead adopted a consumption-based approach to account for the FEWC impacts of the food waste throughout the agri-food supply chain (i.e., including the

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[1] Based on goal 243 (2034): 20% of food consumed in the city comes from sustainable producers in the city region and goal 352 (2040): 15% of Bristol's annual fruit and vegetable supply comes from a network of market gardens and farms within the city.

[2] The plan apparently assumes that 25% of total household food waste ends up in the residual waste. However, the available data and simulation model infers the amount to be likely 40% (or 40 kg/p/y). Hence, we assume 3% annual reduction (36% by 2030) which is in between of both estimates.

Table 1
Overview of simulation scenarios.

Scenario	Description[a]	Parameter Change[b]	Population Growth[b]	HaFS Growth[b]
$B_{constant}$	constant baseline reference with no population growth or HaFS growth	default parameter values	–	–
I1	food waste reduction five sub-scenarios $I1_{HH}$, $I1_{H}$, $I1_{R}$, $I1_{M}$, $I1_{PP}$	Reduction +2%	–	–
I2	increased redistribution four sub-scenarios $I2_{H}$, $I2_{R}$, $I2_{M}$, $I2_{PP}$	Redistribution +2%	–	–
I3	increased animal feed four sub-scenarios $I3_{HH}$, $I3_{R}$, $I3_{M}$, $I3_{PP}$	Animal Feed +2%	–	–
I4	increased composting five sub-scenarios $I4_{HH}$, $I4_{H}$, $I4_{R}$, $I4_{M}$, $I4_{PP}$	Compost +2%	–	–
I5	increased AD five sub-scenarios $I5_{HH}$, $I5_{H}$, $I5_{R}$, $I5_{M}$, $I5_{PP}$	AD +2%	–	–
I6	increased incineration five sub-scenarios $I6_{HH}$, $I6_{H}$, $I6_{R}$, $I6_{M}$, $I6_{PP}$	Incineration +2%	–	–
I7	increased landfill five sub-scenarios $I7_{HH}$, $I7_{H}$, $I7_{R}$, $I7_{M}$, $I7_{PP}$	Landfill +2%	–	–
B_{growth}	dynamic baseline reference with population growth and HaFS growth	default parameter values	0.6%	1.5%
P1	Courtauld Initial	Household: Reduction +1.4% Animal Feed +1.4% HaFS: Reduction +1.8% Redistribution +1.8% Retail and Manufacture: Reduction +1.2% Redistribution +1.2% Animal Feed +1.2%	0.6%	1.5%
P2	Courtauld Optimal	Household: Reduction +2% Animal Feed +0.8% HaFS: Reduction +2.5% Redistribution +1.1% Retail and Manufacture: Reduction +1.1% Redistribution +1.8% Animal Feed +0.7%	0.6%	1.5%
P3	NetZero 2050	Electricity Emission Factor −6.5%	0.6%	1.5%
P4	Bristol One City – Urban Farming	Local Production to Household +1% Local Production to HaFS +1%	0.6%	1.5%
P5	Bristol One City – AD Increase	AD +3%	0.6%	1.5%
P6	Bristol One City – Water Reduction	Household Water Use −1%	0.6%	1.5%
P7	Combined – Sum P2–P6	P2+P3+P4+P5+P6	0.6%	1.5%

[a] Indices of sub-scenarios in I1–I7 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.

primary production sector). Despite existing uncertainties around the amount of food waste in primary production, this approach can depict a more comprehensive picture of the real impacts of the urban food system (details in Section A1.3 in Supplementary Materials). Full details of data sources, equations, and assumptions are available in Appendix 2.

Overall, the net energy, water, and carbon footprints of 371,200 tonnes food produced for Bristol are 1,432,600 MWh, 25, 630, 300 m^3, and 811,400 tonnes CO_{2e}, respectively. To put these into context, the energy footprint of Bristol's food is more than one fifth of total energy consumption of the city in 2018 (BEIS, 2021c). Similarly, the water footprint of food in Bristol is significantly higher than the water usage of the urban households (Wessex Water, 2019). In terms of carbon footprint, the annual Bristol food supply chain emission is more than half of the territorial CO_2 (excluding other GHGs) emission of the city in 2018 (BEIS, 2021d).

When considering the agri-food supply chain, more than one fifth of the food which was produced for Bristol consumption (i.e., 81,200 tonnes) ends up being wasted and another 6% is fed to animals (Fig. 3a). As the main consumer, households account for 57% of the overall food waste generated (i.e., 46,300 tonnes per year). The HaFS sector is estimated to generate 11,800 tonnes annually which is equal to 14% of Bristol's food waste. In the process of meeting consumer demand in Bristol, a total of 23,100 tonnes of food is wasted in primary production, manufacture, and retail sectors, respectively accounting for 15%, 11% and 3% of the total urban food waste.

Moreover, it is estimated that 22,600 tonnes of food which was intended for human consumption is fed to animals, while only less than 400 tonnes of commercial food surplus is redistributed to households (Fig. 3a).

From total Bristol food waste, 19,900 tonnes is being sent to AD plants, of which 70% comes from the households. The rest of food waste, it is estimated, is either collected as part of general waste (i.e., 29,800 tonnes incinerated, and 9300 tonnes landfilled), or treated at the source (i.e., 11,600 tonnes composted, and 10,600 tonnes disposed in sewer) (Fig. 3a).

In terms of energy footprint, Household is the biggest energy consumption sector. Factoring in the scale of food inflow at each sector, however, HaFS -with 4.48 MWh per tonne of food-uses 2.6 times more energy than household for an equal amount of food purchased. Hence, it is the most energy intensive sector (Fig. 3b). The food supply sectors, including primary production, manufacture, and retail, account for roughly half of the gross energy footprint of the food system (9%, 13%, and 24% respectively) (Fig. 3b). Although minimal, energy for water abstraction, waste transport and food surplus redistribution are other factors which increase the gross energy footprint (though only by 1%). In contrast, using food waste to replace animal feed or mineral fertilisers, and to generate energy, reduces the gross energy footprint. Hence, feeding animals, AD, composting, incineration, landfill, and sewer treatment, are all energy recovery measures which directly or indirectly reduces the net energy footprint of Bristol's food waste by 32,600 MWh per year (Fig. 3b).

Blue water abstraction (i.e., surface and/or groundwater) for primary production has the highest impact on water footprint of Bristol food (Fig. 3c). It accounts for three quarters of the gross water footprint in the system. Household water consumption is the second key contributor to the water footprint (i.e., 12%). Although the total water footprint of HaFS is around half of household consumption, its water intensity (i.e., consumption per tonne of food) is 1.9 times higher than the household's. Water abstraction for generating the electricity consumed throughout the supply chain accounts for around 1% of the gross water footprint, which although insignificant, adds much more to

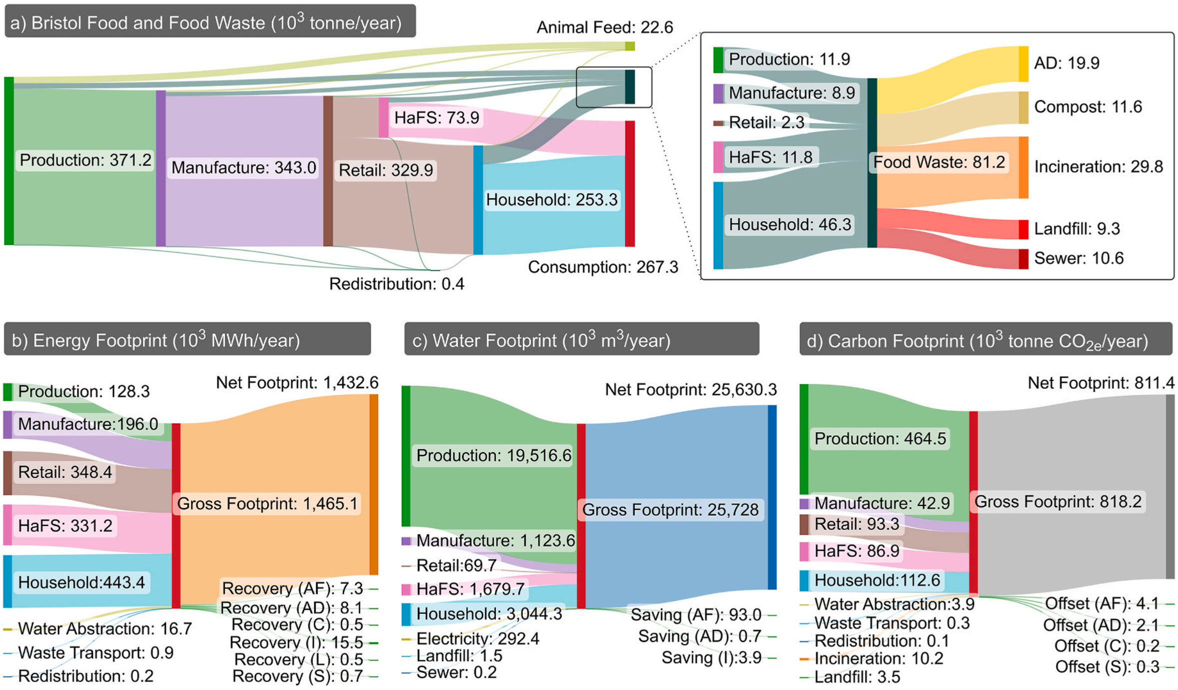

Fig. 3. Sankey charts of flow of food and food waste (a), and its energy - (b), water - (c), and carbon - (d) footprint in Bristol. *(AF: Animal Feed, AD: Anaerobic Digestion, C: Compost, I: Incineration, L: Landfill, S: Sewer)*

the gross water footprint than the retail sector. This also explains the importance of electricity generating measures (i.e., AD, incineration, and landfill), or the electricity-demand reducing measures (i.e., replacing animal feed or fertiliser) for decreasing gross water footprint of the system (Fig. 3c).

Primary production is also the biggest single carbon emitter in the supply chain, accounting for 57% of Bristol's gross carbon footprint in the food sector (Fig. 3d). Comparing this to the low energy footprint of the sector, it is worth mentioning that emissions from stationary and mobile combustion accounts for only 10% of total agricultural emissions. The vast majority of the emissions in primary production comes from livestock enteric fermentation and wastes, soils, and land use and land use change (i.e., cropland) (BEIS, 2021e). Although energy generation from food waste at incineration and landfill reduces the total energy footprint, they are nonetheless net carbon emitters that contribute to the gross carbon footprint of Bristol's food (Fig. 3d). On the other hand, animal feed, AD and composting are net carbon sink measures which reduce the carbon footprint by replacing feed production, electricity generation and fertiliser manufacturing, respectively (Fig. 3d).

3.2. *Energy, water and carbon dynamics of food waste in Bristol*

The various food waste management strategies (Scenarios I1– I7) have different dynamic impacts on energy, water, and carbon footprints (Fig. 4). As indicated in Table 1, each specified hypothetical scenario assumes a 2% per year linear increase in one treatment option. Since the rate of food demand and waste generation during the simulation period are assumed to be constant, the system is in equilibrium and the baseline scenario in all the charts illustrates a straight horizontal line from year 0 to year 12 (Fig. 4). A descending scenario trend in the blue area indicates a lower energy, water, or carbon footprint, and hence is a more preferable option. Although the system is in equilibrium, linear reduction and redistribution scenarios (Scenarios I1 and I2) do not necessarily exhibit a linear behaviour (i.e., curve lines in Fig. 4). This is because any reduction in demand (Scenario I1) in the short term leads to overstocking on the supply side; this forces the supply side to reduce their resource use immediately. This results in a sharp drop in FEWC footprints before the supply chain reaches a new equilibrium. This bottom-up effect of reduction fades away at the upstream supply chain. Similarly, food surplus redistribution (Scenario I2) also reduces household food demand and, hence, follows the same dynamics.

Regarding household food waste, the simulation results explicitly indicate that the reduction scenario (Scenario I1; see Table 1 for scenario specifications) has the lowest energy, water, and carbon footprint (Fig. 4a,b,c). By the end of the simulation period, the 2% annual reduction scenario decreases urban food waste by 17.2% (11,800 tonnes), and total energy, water, and carbon footprints by 2.9% (42,100 MWh), 4.7% (1,192,500 m^3), and 4.1% (33,600 tonne CO_{2e}), respectively. After the reduction scenario, pet feed replacement (Scenario I3) has the most promising impact across energy, water, and carbon footprints (Fig. 4a,b,c). With 1.5%, 0.3% and 1.2% decrease in energy, water, and carbon footprints at the end of the simulation, the pet feed scenario illustrates higher impacts on energy footprint than water and carbon footprints. In fact, the household water footprint chart (Fig. 4b) shows that except reduction (Scenario I1), no other scenario has a significant impact in changing the water footprint of the system. It is because almost all of the total water footprint comes from the agri-food supply chain with primary production accounting for 76%, while food waste management and electricity generation have a very small impact.

After reduction and animal feed scenarios, the preferability of other scenarios (Scenario I4-7) in the household sector is neither as high nor as straightforward. While these scenarios have almost no impact on water footprint, a trade-off emerges between carbon and energy footprints where the electricity generation/replacement factor plays a determining role. Given that, although AD (Scenario I4) is more preferable than incineration (Scenario I6) in terms of carbon footprint, it generates less electricity (i.e., 0.41 MWh/tonne of food waste treated compared to 0.53 MWh/tonne of waste incineration), hence slightly less preferable according to the energy footprint (Fig. 4a,c). Similarly, home composting (Scenario I5) -which as a net carbon sink option is more preferable than the baseline, incineration, and landfill scenarios (Fig. 4c)- has a higher energy footprint (Fig. 4a and b) because any increase in composting reduces the electricity generation potential of other treatment options. Incineration (Scenario I6), on the contrary, has a promising

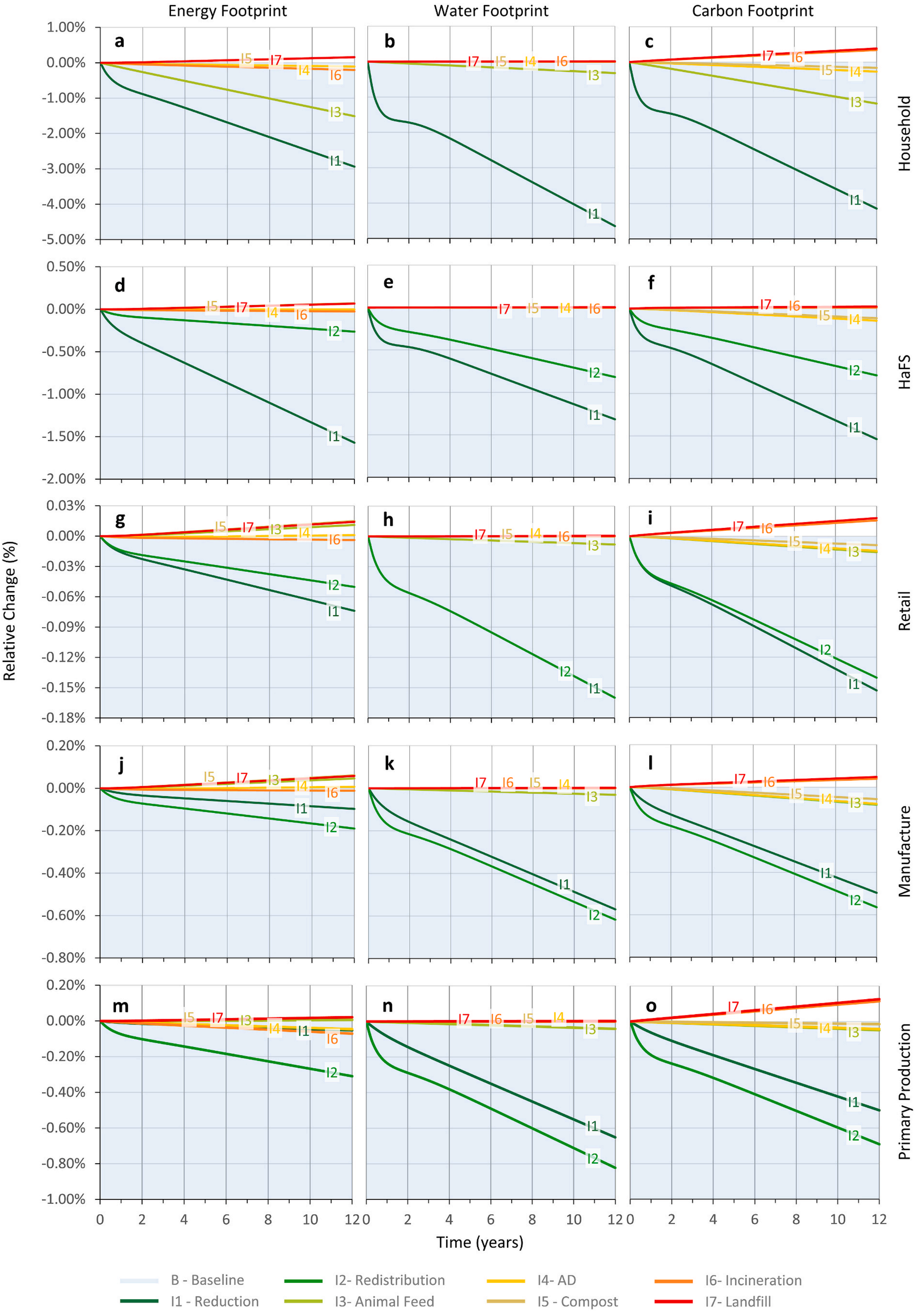

Fig. 4. Energy, water, and carbon footprints of Bristol food in household, hospitality and food service (HaFS), retail, manufacture, and primary production. Footprints are depicted as percentage change in consumption (energy, water) or emissions (carbon) relative to the baseline scenario. Blue shading shows area of beneficial impact (i.e., negative relative change).

impact on energy footprint while worsening the carbon footprint significantly (Fig. 4a,b,c). Landfill (Scenario I7), despite a net energy generation fraction of 54 kWh/tonne (Jeswani and Azapagic, 2016), is the least preferable option overall.

Showing similar dynamics to the household case, HaFS food waste reduction (Scenario I1, Fig. 4d,e,f) has the lowest energy, water, and carbon footprint among HaFS scenarios. The 24% reduction in the final year of simulation can reduce the rate of urban food waste and energy, water, and carbon footprint of the food sector by 4.3% (3500 tonnes), 1.6% (22,500 MWh), 1.3% (337,500 m^3) and 1.5% (12,500 tonne CO_{2e}) per year, respectively. The second-best option for HaFS surplus and waste management across all FEWC footprints is redistribution. Although redistribution (Scenario I2) does not affect HaFS sector dynamics, it reduces household food purchase and hence shrinks the total food system. Nevertheless, it is less preferable than reduction because redistribution does not reduce demand (i.e., it only reduces household purchase) while the reduction of HaFS food waste reduces its demand. Moreover, the high resource intensity of HaFS compared to the household scenario as well as the additional redistribution operational footprints are other factors which makes redistribution a less favourable option.

Since the baseline scenario assumes that three quarters of food waste in the HaFS sector is incinerated, an increase in AD proportion (Scenario I4) can lower the sector's carbon footprint while leading to a slightly higher energy footprint due to the aforementioned trade-off between AD versus incineration treatments (Fig. 4d,e,f). Similar to the household scenarios, composting (Scenario I5) is the fourth preferable option to mitigate the carbon footprint (Fig. 4f), with landfill (scenario I7) still showing the poorest results. For the very same reason discussed for the household sector, apart from reduction and redistribution (Scenario I1 and I2), the impact of other HaFS scenarios on the water footprint is not tangible.

Regarding the retail sector (Fig. 4g,h,i), food surplus reduction (Scenario I1) continues to be the most preferable option. Based on water footprint (Fig. 4h), however, redistribution (Scenario I2) is as preferable as reduction (Scenario I1). While the reduction and redistribution scenarios are governed by the same dynamics, the energy, water, and carbon footprints of the redistribution process makes the latter slightly less preferable. Even though using food waste to replace livestock feed (Scenario I3) has the third lowest water and carbon footprints (Fig. 4h and i), it is generally less efficient than the pet feed option at the household stage, with one of the highest energy footprints in retail scenarios (Fig. 4g). While the baseline scenario assumes that half of retail food waste is currently sent to AD and the other half incinerated, any increase in the AD option (Scenario I4) reduces the carbon footprint (Fig. 4i) at the cost of a higher energy footprint (Fig. 4g), and vice versa. Similarly, composting (Scenario I5), incineration (Scenario I6), and landfill (Scenario I7) show identical behaviour to the corresponding scenarios for household and HaFS.

In the manufacture sector (Fig. 4j,k,l), unlike previous sectors, the reduction (Scenario I1) lags behind the surplus redistribution scenario (Scenario I2) in all three dimensions. This is because the redistribution of manufacture surplus reduces household food purchase and less purchase leads to smaller food supply sectors (i.e., retail, manufacture, and primary production). The reduction scenario, however, can only shrink manufacture and primary production sectors (i.e., does not affect the retail sector). As such, redistribution (Scenario I2) shrinks the supply chain by 2800 tonnes at the end of the simulation, compared to 2600 tonnes shrinkage caused by reduction (Scenario I1). This relative advantage of redistribution over reduction at manufacture is high enough to compensate the operational footprint of the redistribution process and yet to outpace the benefits of the reduction scenario (Fig. 4j, k,l). The rest of the scenarios behave similarly to the retail sector.

Finally, in the primary production sector (Fig. 4m,n,o), redistribution (Scenario I2) significantly outperforms the environmental gains of reduction and all other scenarios due to reasons explained above. Although reduction (Scenario I1) has the second lowest water and carbon footprint, the total energy which it saves is slightly less than incineration (Scenario I6). This is because the net energy use per tonne of food waste reduction at primary production stage is lower than the net energy production pet tonne of food waste incineration (Fig. 4m). The remaining scenarios follow the same pattern as previous sectors.

3.3. Impacts of urban policies on the FEWC nexus

The purpose of this section is to analyse the impacts of the Courtauld Commitment 2030 (Wrap, 2022), the UK Net Zero Strategy (BEIS, 2021a) and the Bristol One City Plan (Bristol One City, 2021) on the FEWC nexus in Bristol (see Table 1 for scenario specifications). In addition to energy, water, and carbon footprints, the impacts of these policies on Bristol's food and food waste are illustrated (Fig. 5). To comply with the post-farm-gate approach of the policies, primary production surplus and waste are not added to the food waste figures in this section. All the policy scenarios (P1–P7) are compared against a baseline scenario (Scenario B_{growth}) which assumes 0.6% and 1.5% annual growth in household and HaFS sectors, respectively. As a result of growth in consumption, the urban food footprint is estimated to increase from 371,200 tonnes in 2018 to 419,200 tonnes in 2030 (Fig. 5a). Due to accumulative delay at each stage of the supply chain, a linear growth in demand in the short term puts more pressure on the supply sectors' stocks. To respond to increasing demand and compensate the shortfall, the food supply rate increases sharply before reaching an equilibrium. The curved scenario trends in food, energy, water and carbon footprints (Fig. 5a,d,e) demonstrate these dynamics.

Moreover, as discussed in the previous section, apart from feeding household leftovers to pets, the preferability of using commercial food to replace livestock feed is not as high as the results of reduction and redistribution. Despite this, the literature (including the above policies) recognises the animal feed option as 'food surplus' and a prevention strategy, along with reduction and redistribution measures (i.e., not as 'food waste'). To address this, Fig. 5 illustrates two graphs of post-farm-gate food waste, where the first (Fig. 5b) assumes that using discarded food as animal feed is not 'food waste', while the latter (Fig. 5c) does count it as food waste. Labelling the animal feed as 'food waste' would add the 6300 tonnes of discarded food that is fed to animals to the estimated 69,400 tonnes post-farm-gate food waste (Fig. 5a vs. 5 b).

Compared to the baseline scenario, Courtauld Initial (Scenario P1; see Table 1 for details) reduces urban food waste by 18,400 tonnes while replacing 9400 tonnes of animal feed at the end of the simulation period. This can cut annual food, energy, water, and carbon footprint rates by 25,100 tonnes, 71,300 MWh, 1,623,100 m^3, and 54,200 tonnes CO_{2e} by 2030, respectively (Fig. 5d–f). Courtauld Optimal (Scenario P2), however, outperforms these gains by assuming a more targeted policy in which the main focus is on reduction at consumer and redistribution at supply sectors, rather than the animal feed option. Although both Courtauld scenarios are in line with the Courtauld Commitment 2030, Courtauld Optimal reduces food waste by 23,300 tonnes while increasing the animal feed option by only 5400 tonnes in the final year of simulation. This optimisation can help to save an additional 6600 tonnes of food, 13,800 MWh energy, 425,400 m^3 water, and 10,600 tonnes CO_{2e} to the Courtauld Initial (Scenario P1) gains. Nevertheless, despite encouraging results from both Courtauld scenarios, the gains lag behind increasing growth in food, energy, water, and carbon footprints caused by the growth in urban food demand (Fig. 5d–f).

Depicting the impacts of decarbonising grid electricity, the Net Zero 2050policy (Scenario P3; see Table 1 for details) offers the greatest potentials for reducing the carbon footprint of Bristol food. Adhering to the Net Zero 2050 target can dramatically mitigate the carbon footprint of the urban food sector, by 95,700 tonnes CO_{2e} in 2030 (Fig. 5f). This also indicates that the success of Bristol's One City Climate Strategy, which aims to be carbon neutral by 2030, would decrease the carbon footprint even further compared to the current UK N et Zero 2050

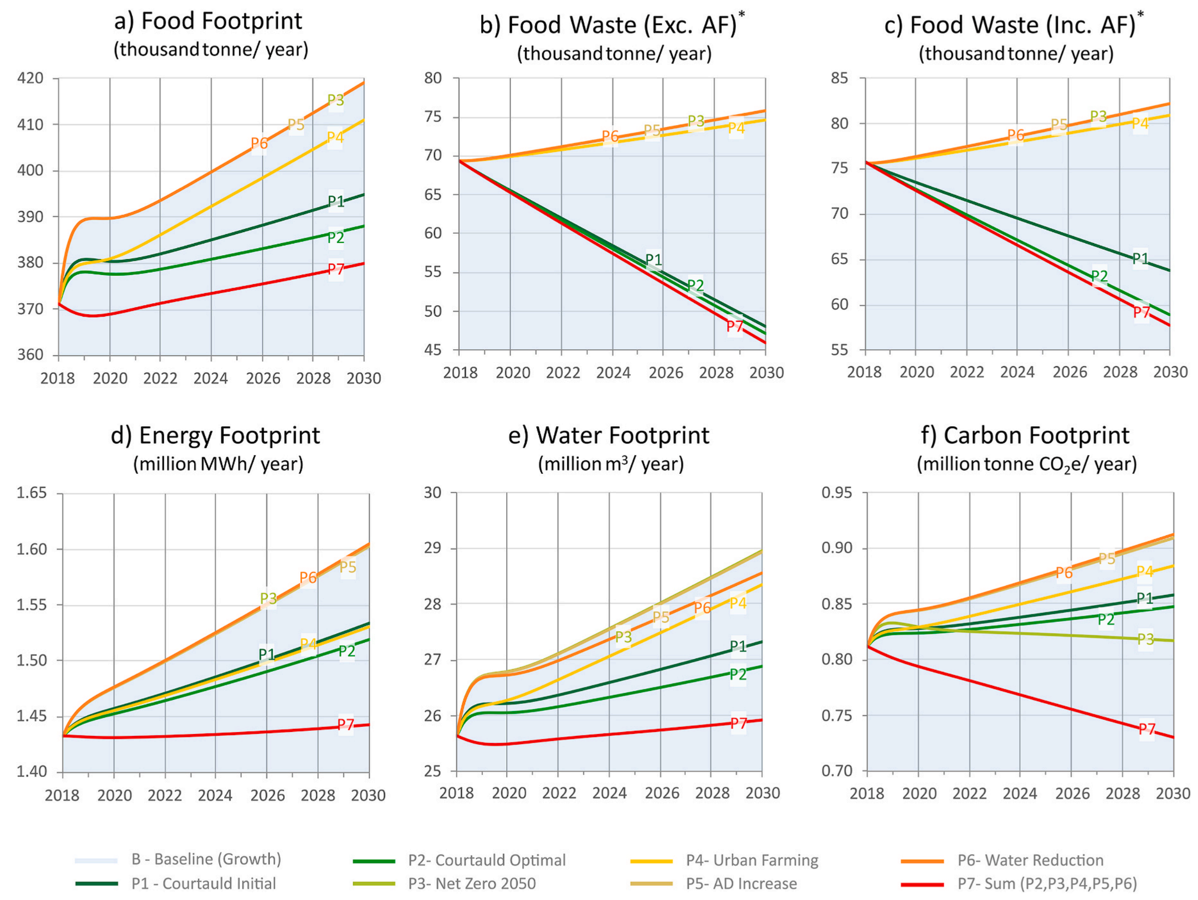

Fig. 5. Impacts of policies on food, energy, water, and carbon footprints in Bristol. Blue shading shows area of beneficial impact (i.e., negative relative change). Please note the different values and measurement units on the y-axes. * Primary Production food waste is not included (AF: Animal Feed).

scenario (Fig. 5f). Given the consumption-based approach of this study and the geographical diversity of food sources, however, effective cutting of the environmental footprint of food consumed in Bristol requires global and national decarbonisation initiatives in addition to the Bristol carbon neutral strategy.

Increasing urban farming and local food production, as per the Bristol One City policy (Scenario P4), is also a promising policy for shrinking FEWC footprints of the Bristol's food. The 1% per year increase in direct supply of produced food to consumers will downsize the food sector by 8200 tonnes in 2030. Hence, the energy, water and carbon footprints of the system would be 74,400 MWh, 604,200 m^3, and 28,400 tonnes CO_{2e} lower than the baseline scenario (Fig. 5d–f).

Two other options in the Bristol One City policy, i.e., increasing the AD treatment of household food waste (scenario P5), and reducing household water consumption (Scenario P6), are also useful measures, but with a much lower positive impact on the FEWC footprint comparing to previous scenarios. By 2030, AD increase (Scenario P5) can save 2300 MWh energy and 3300 tonne CO_{2e} with almost no effect on food and water footprints. On the contrary, household water reduction (Scenario P6) can decrease water use by 395,200 m^3 with no benefits to food, energy, and carbon footprints.

While no single scenario has the potential to decrease FEWC footprints in a growing demand context, Scenario P7 shows that the combination of the Courtauld Optimal, Net Zero 2050, Urban Farming, AD increase and Water Reduction (Scenarios P2–P6) can shrink (or at least slow down) the environmental impacts of the food sector (Fig. 5).

3.4. Optimisation of the food waste hierarchy

Beyond the modelling insights for Bristol city, the purpose of this paper was to study the impacts of urban food waste management on whole FEWC nexus, and so to re-think the traditional waste hierarchy framework (Fig. 1). The structure and dynamics of the developed model encompass generic feedback loops within the FEWC system in urban areas. Moreover, the data points on efficiency of each treatment option and the impacts on FEWC footprints are generally extracted from the scientific literature and national datasets (Appendix 2; Table A2.11). These ensure that the modelling insights can effectively be applicable to other urban circular economies. Comparing the food waste hierarchy framework against our findings, the traditional hierarchy appears to be a generally useful guidance to reduce the food waste and its carbon footprint. Such a simplistic framework, however, can have its shortcomings. We find that the hierarchy is not always fit to guide the most effective environmental policies as it lacks accuracy and robustness when it comes to details. In particular, our findings suggest that a useful and robust visualization of the food waste hierarchy needs to be able to illustrate: (i) the relative preferability of waste management options in each sector; (ii) the impacts of each option on energy, water, and carbon footprints of food; and (iii) the scale/comparative advantage of each option. Keeping these in mind, Fig. 6 presents an optimised version of the food waste hierarchy framework (cf. Fig. 1) based on the results reported in Section 3.2. The three hierarchies in Fig. 6 re-illustrate the results in Fig. 4 where the distance between each scenario line relative to the scenario with the highest footprint is translated into preferability area of each option.

Unlike the generic guidance of food waste hierarchy, our findings suggest that the preferability of waste management options can vary from one sector to another. In primary production and manufacture, for instance, the benefits of food waste reduction on the FEWC nexus lags behind redistribution due to the dynamics discussed in Section 3.2. The

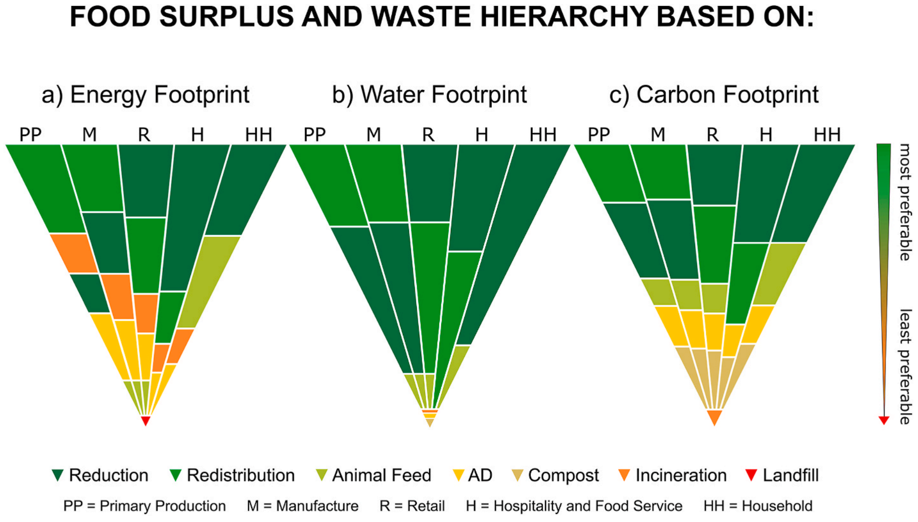

Fig. 6. Optimised version of food surplus and waste hierarchy framework based on the simulation findings. The area of each option represents its preferability weight for different sectors.

reduction option in primary production has an even smaller effect on reducing the energy footprint compared to incineration (Fig. 6a).

While reduction and redistribution in the retail sector have similar dynamics, adding the operational footprints of redistribution (0.61 MWh, 0.02 m^3, 0.186 tonne CO_{2e} per tonne of food) makes it a slightly less favourable option than reduction. It is worth noting that the model assumes no added environmental impacts for the reduction option while in reality, application of any systemic reduction strategy might have a minimum environmental cost. Factoring in the potential footprints of reduction as well as the possibility of lowering redistribution operational costs, redistribution can be seen as an equally preferable option compared to reduction in the retail sector. Considering the high environmental costs of redistributing food from HaFS as a resource-intensive consumer sector to household, however, the preferability of reduction soars much higher than redistribution in this sector. Hence, in general, increasing redistribution in the supply sectors while reducing food waste win consumer sectors appears to be the most preferable approach to reduce the environmental impacts of food.

Food surplus redistribution in the UK upstream supply chain has not only a high environmental preferability, but also a huge potential. The total edible food wasted in the manufacturing sector in the UK, for instance, was around 800,000 tonnes in 2018 of which less than 5% was redistributed to people (WRAP, 2020a). On the flip side, however, it is worth noting that this option does not provide a comprehensive solution to the urban food waste problem. Even ignoring redistribution's regulatory, technical, and practical limitations, the potential redistributable surplus is always restricted to 'edible food'. Referring to the above example, only 53% of food surplus and waste in the UK manufacture sector is 'edible' (WRAP, 2020a), which means even a perfect redistribution system can only address around half of the manufacture food surplus and waste (Fig. 7). Hence, maximising redistribution in this research is recommended as an interim strategy for food waste management. Adopting a systemic approach to avoid overproduction and to prevent food waste generation in the first place is the most preferable option for a 'food utopia' scenario (e.g., Papargyropoulou et al., 2022), as this affects both edible and inedible food waste.

Next, one major limitation of the current food waste hierarchy is its reductionist approach which fails to account for the impacts of food waste on other sectors. As illustrated in the optimised version of the hierarchy, the level of preferability of different food waste management options can vary from one nexus element to another (Fig. 6). While the order of options for mitigating the carbon footprint resembles the traditional hierarchy (Fig. 6c), prioritising the energy footprint, for instance, reshuffles it remarkably (Fig. 6a). In an energy-oriented food waste management approach, incineration with 0.48 MWh/tonne net energy generation capacity would be the second most preferable option for primary production, and third for other sector's food surplus and waste management (Fig. 8). In contrast, the livestock feed and compost options move down in the hierarchy. Although converting food waste to livestock feed and compost is a useful way to reduce animal feed and mineral fertiliser production footprints, the energy savings of these options are significantly lower than the displaced electricity generated in incineration and AD options. Unlike livestock feed, however, replacing pet feed at household level seems to be a favourable option to reduce not only energy, but also the water and carbon footprints of the system (Fig. 6). This is mainly due to the high resource intensity of pet food production (FEDIAF, 2018), and to some extent, the on-site treatment of the food waste (i.e., less collection and treatment costs).

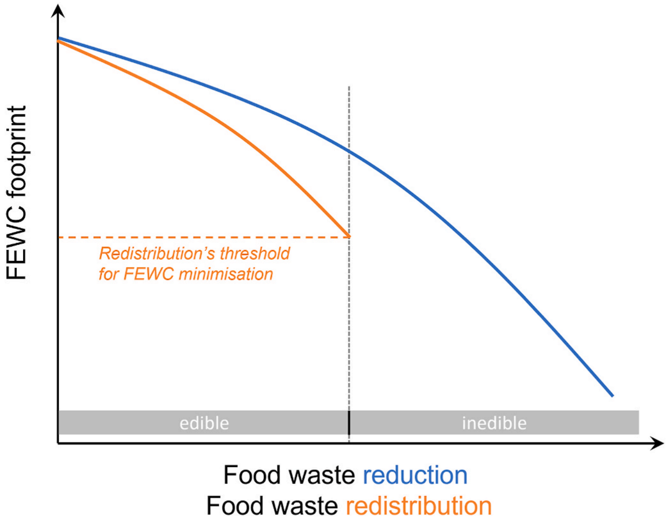

Fig. 7. Food waste reduction and redistribution potentials in upstream supply chain where the environmental benefits of the food surplus redistribution in the short term outperforms the reduction benefits. Unlike the reduction option, the redistribution potential, however, is restricted to edible food.

Another major gap of the typical food waste hierarchy which is addressed in our optimised version (Figs. 6 and 8) is the limitation to illustrate the scale of preferability of each food waste management

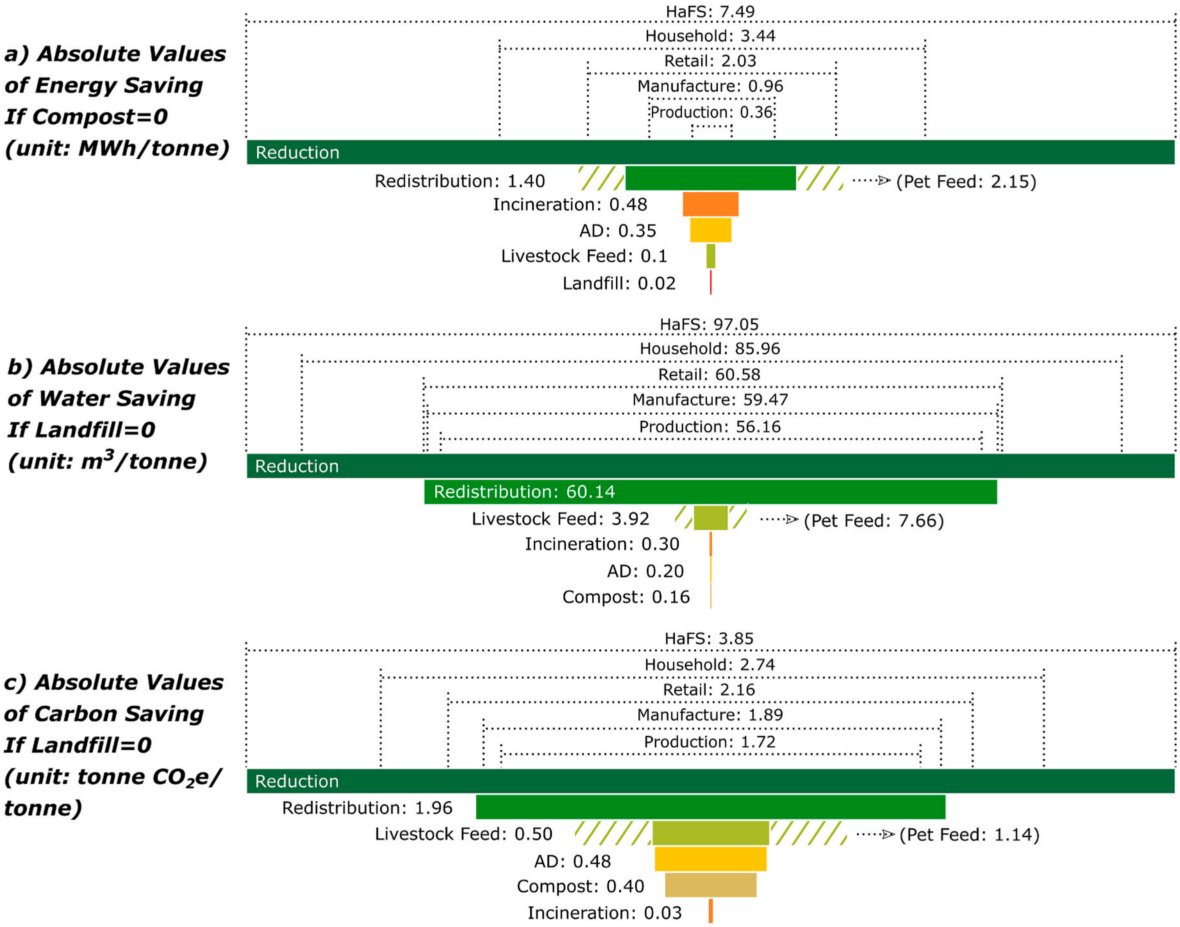

Fig. 8. Optimised food waste hierarchy based on absolute value of energy, water, and carbon savings. The quantities show the comparative advantage of treating one tonne of food surplus and waste over the least preferable option.

option. The proposed food waste hierarchy in this study shows not only the scale of preferability of each option (Fig. 6), but also its numeric value comparing to the least preferable option (Fig. 8). Depicting the absolute values of difference between the least preferable option and alternative scenarios (Fig. 8) facilitates a more in-depth comparison of the food waste management options.

In terms of energy footprint, for instance, reducing 1 tonne of food waste has between 0.36 MWh (in primary production) and 7.49 MWh (in HaFS) advantage over composting (Fig. 8a). This significant difference between absolute energy gains of two sectors in the supply chain echoes that the one-size-fits-all approach of traditional food waste hierarchy is not fit for guiding the most effective policies in all agri-food sectors. As such, regarding the 1.4 MWh comparative advantage of redistribution, a robust hierarchy framework should be able to highlight its high preferability in the supply sectors.

Adding the absolute values of water saving in the optimised hierarchy explicitly demonstrates the substantial advantage of reduction and redistribution over other treatment options (Fig. 8b). The 60.14 m^3/tonne absolute value of redistribution, for instance, indicates that this option saves at least 15 times more water than feeding livestock and 200 times more than the next treatment options.

As different food waste management options have different carbon footprints, there are corresponding impacts on relative carbon savings for treating 1 tonne of food. Thus, landfilling and incineration are the least preferable options, while composting, AD and livestock feed save 0.4–0.5 tonne CO_{2e} per tonne of food waste treated (Fig. 8c). Again, reduction and redistribution are the most preferable options. Although the comparative advantage of the redistribution's carbon saving is not as high as its water saving advantage, our optimised framework shows that redistributing 1 tonne of food surplus has 4–5 times more advantage over the next best options in carbon savings (Fig. 8c).

Overall, the visual dominance of green colour in the optimised version of the hierarchy (Fig. 6) along with their numeric values (Fig. 8), clearly conveys that the scale of difference between most preferable and least preferable options is huge.

Looking at the scales, it can also be inferred that there is no clear line to distinguish between 'food surplus' and 'food waste' in terms of their environmental impacts. Hence, categorising reduction, redistribution and animal feed as food surplus and the rest of the options as food waste seems to be a more subjective classification. Given that, despite the different levels of preferability between pet feed and livestock feed options, classification of 'animal feed' as 'food surplus' and a 'prevention' strategy in the literature requires a critical revision. This was also raised during the interview process when interviewee H argued that '[food surplus and] waste can be defined in different ways but feeding animals or plants [composting] could be seen at least as equal'. According to one definition, food is 'any substance that is – or was at some point – intended for human consumption' (WRAP, 2020b). Building on this, we suggest that food waste should be defined as 'any food (including the inedible parts) that are not consumed by humans regardless of their destination'. This challenges the idea of defining food waste based on its destination, where if the food is redistributed, fed to animals, or converted into industrial products, it is considered as food surplus (and not food waste). Labelling the animal feed option as food surplus and a prevention strategy can boost the incentives to feed edible human food to animals at cost of less redistribution which is against the evidence-based recommendation of this study.

4. Conclusion

To explore the environmental impacts of urban food waste management, this study developed a detailed simulation model of FEWC dynamics in the city of Bristol. We simulated two set of scenarios to compare the FEWC impacts of food waste hierarchy's options on one hand (Section 3.2), and the relevant national and local policies on the other hand (Section 3.3). The insights from the model, were then used to present an optimised version of the food waste hierarchy (Section 3.4).

Regarding the policy scenarios, the results highlight that reducing the environmental impacts of food (waste) requires a systemic approach with multiple policy initiatives. The policies, as shown in section 3.3, should generally focus on food waste reduction at the consumer level, and redistribution at the supply level. Urban farming and local production of food, as well as decarbonising electricity and carbon neutrality by 2030, as outlined in the Bristol One City Plan, can significantly reduce the FEWC footprint of the city. Increasing AD treatment of household food waste and reducing household water consumption are additional positive measures with smaller gains for the FEWC nexus.

The simulation model results also show that the current CE's waste hierarchy may be failing to guide the most promising environmental policies because: 1- it does not account for the impacts of food waste on energy and water resources, 2- it fails to prioritise the best waste management options based on the different dynamics of each waste generating sector, and 3- it does not specify by how much a given waste management option is more/less preferable over another. We conclude that the current food waste hierarchy is not sufficient to lead to the environmental sustainability.

We propose an improved version of the food waste hierarchy framework that addresses the impacts of food waste on the FEWC nexus in urban CEs (Figs. 6 and 8). This new framework indicates that focusing on reduction in downstream and redistribution in upstream supply chain are the best waste management measures, not only because they have significantly higher positive impacts compared to other measures, but also because they can reduce the impacts across all FEWC sectors. Moving to the next preferable options is more ambiguous and leads to a trade-off between carbon and energy footprint, where any gain in carbon emission is at risk of increasing the energy footprint, and vice versa.

Additionally, building on the simulation results, workshops and interviews, and on existing studies, our new framework argues that using human food to feed animals should be regarded as 'food waste' rather than 'food surplus'. Hence, it is proposed that food waste should be defined as 'any food and inedible parts which are not consumed by humans regardless of their destination'.

Finally, this research is –to the best of our knowledge– the first dynamics modelling of food waste management impacts in a CE context. To reflect on this experience, developing a data-oriented simulation model of the complex dynamics in FEWC nexus can provide useful insights for better understanding and managing the system. Lack of local data, and inconsistency/incompatibility between data sources, however, has been a major challenge for this study. Whilst this study focused on the environmental impacts of urban food waste on the FEWC nexus, it does not address the socio-economic dimensions. Further research is warranted to better comprehend the social and economic impacts of modifying the food waste hierarchy in urban CEs.

Author contributions

Ali Parsa: Conceptualization, Methodology, Formal Analysis, Investigation, Resources, Writing – Original Draft, Visualization. Marco Van De Wiel: Conceptualization, Methodology, Validation, Writing – Review & Editing, Visualization, Supervision. Ulrich Schmutz: Conceptualization, Methodology, Writing – Review & Editing, Supervision. Jana Fried: Conceptualization, Methodology, Writing – Review & Editing, Supervision. Daniel Black: Resources, Writing – Review & Editing. Ian Roderick: Resources, 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

The data is available in the supplementary materials.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2023.118554.

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