



Environmental sustainability in the food-energy-water-health nexus: A new methodology and an application to food waste in a circular economy

Peter C. Slorach, Harish K. Jeswani, Rosa Cuéllar-Franca, Adisa Azapagic*

Sustainable Industrial Systems, Department of Chemical Engineering and Analytical Science, The University of Manchester, Manchester M13 9PL, UK

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ABSTRACT

Current studies on the food-energy-water nexus do not capture effects on human health. This study presents a new methodology for assessing the environmental sustainability in the food-energy-water-health nexus on a life cycle basis. The environmental impacts, estimated through life cycle assessment, are used to determine a total impact on the nexus by assigning each life cycle impact to one of the four nexus aspects. These are then normalised, weighted and aggregated to rank the options for each aspect and determine an overall nexus impact. The outputs of the assessment are visualised in a “nexus quadrilateral” to enable structured and transparent interpretation of results. The methodology is illustrated by considering resource recovery from household food waste within the context of a circular economy. The impact on the nexus of four treatment options is quantified: anaerobic digestion, in-vessel composting, incineration and landfilling. Anaerobic digestion is environmentally the most sustainable option with the lowest overall impact on the nexus. Incineration is the second best option but has a greater impact on the health aspect than landfilling. Landfilling has the greatest influence on the water aspect and the second highest overall impact on the nexus. In-vessel composting is the worst option overall, despite being favoured over incineration and landfilling in circular-economy waste hierarchies. This demonstrates that “circular” does not necessarily mean “environmentally sustainable.” The proposed methodology can be used to guide businesses and policy makers in interpreting a wide range of environmental impacts of products, technologies and human activities within the food-energy-water-health nexus.

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1. Introduction

The food-energy-water (FEW) nexus captures the interconnections and co-dependencies of the three systems and it has been proposed that policy makers should use a nexus approach to help progress the UN's sustainable development goals (Boas et al., 2016). A framework for defining this three-pillar nexus, proposed by Hoff (2011), focuses on achieving climate protection and securing fair access to water, food and energy for all, while encouraging the sustainable growth of a green economy in a rapidly urbanising world. Flammini et al. (2014) provide broad context and conceptualisation of the nexus and use case studies to present an assessment tool for the quantitative analysis of the FEW nexus. The tool includes a set of potential indicators that could be chosen by policy makers in consultation with stakeholders. The Global Water Partnership was an early adopter of the nexus principle with its

Integrated Water Partnership Management concept but, with a water-centric view, it has been criticised for not addressing energy, food and land aspects equally (Ringler et al., 2013). Similarly, the Water-Energy-Food Nexus Tool 2.0 developed by the Qatar Environment and Energy Research Institute aims to address all nexus impacts but its focus is primarily on food security (Daher and Mohtar, 2015), a criticism also made of its previous version (Smajgl et al., 2016). While these early models have drawn some criticism, they have helped to progress the nexus concept. However, the concept is yet to have a universally agreed definition or purpose, as highlighted by two recent review papers (Endo et al., 2017; Zhang et al., 2018).

All nexus approaches require a comprehensive understanding of the system being analysed to identify the resources being used and their impacts on the nexus. Life cycle assessment (LCA) is a well-established technique which considers all the inputs and outputs of a product or process to assess its environmental impacts (ISO, 2006a; ISO, 2006b). LCA has been identified as an important tool for the nexus (McGrane et al., 2018) and has been used

* Corresponding author.

E-mail address: adisa.azapagic@manchester.ac.uk (A. Azapagic).

Nomenclature

AD	Anaerobic digestion	NLT	Natural land transformation
ALO	Agricultural land occupation	OD	Ozone depletion
FE	Freshwater eutrophication	PED	Primary energy demand
FET	Freshwater ecotoxicity	PMF	Particulate matter formation
FEW	Food-energy-water	POF	Photochemical oxidant formation
FEWH	Food-energy-water-health	TA	Terrestrial acidification
GWP	Global warming potential	TET	Terrestrial ecotoxicity
IVC	In-vessel composting	ULO	Urban land occupation
LCA	Life cycle assessment	WD	Water depletion
MCDCA	Multi-criteria decision analysis		
MD	Metal depletion		
MET	Marine ecotoxicity		

previously to assess the impact on the food-energy-water (FEW) nexus of different products and processes. Some examples include breakfast cereals (Jeswani et al., 2015), biomass gasification (Al-Ansari et al., 2016) and biogas from energy crops (Pacetti et al., 2015). Karabulut et al. (2018) have expanded the FEW nexus to include land and ecosystem in relation to food security, proposing a matrix for identifying hotspots in each nexus area. LCA is used to determine the impact of different energy, land and water uses related to food production. These resources are ranked individually from negative to positive for their effect on different ecosystem provisions. While this is a useful visual tool for qualitative hotspot analysis within the nexus, it is lacking an overall quantitative impact on the nexus.

Several LCA studies have also focused on food waste in the context of the FEW nexus. For instance, Kibler et al. (2018) have proposed a high level conceptual model for assessing the impacts of the food supply chain and waste on the nexus. The authors conclude that there is a need for a quantitative assessment of food waste management within a nexus framework. Wang et al. (2018) have also considered a nexus approach to urban waste management, but focusing mainly on monetary costs and carbon emissions.

Laso et al. (2018) have expanded the FEW nexus to include a climate change component and assess waste management in the anchovy canning industry in comparison with landfilling, incineration and valorisation of the waste as fish feed (sea bass). One indicator is used to assess each nexus aspect: water consumption for water; global warming potential for climate change; energy consumption for energy; and the amount of protein in waste for the food aspect. This approach captures the impacts on water, climate change and energy but the food aspect indicator is very specific to the studied system and would be difficult to apply to other systems. Furthermore, each of these studies has developed a nexus model specific to the systems being considered, making it difficult to draw wider comparisons of their impact on the nexus.

As far as the authors are aware, no previous studies have attempted to incorporate human health into a nexus assessment despite its importance for human well-being and quality of life. The World Health Organization (WHO, 2016) estimate that one in nine deaths are attributable to health conditions related to air pollution, with approximately three million deaths ($\approx 5\%$ of global annual deaths) solely attributable to ambient air pollution. A further 1.6 million lives are lost annually through exposure to toxic chemicals in the environment that the WHO (2018a) deem preventable through better management and reduction in chemicals use.

Therefore, this paper presents a new methodology which integrates for the first time the health aspect within the food-water-energy (FEW) nexus to determine the life cycle environmental

impacts of products, technologies or human activities on each of the four aspects of the nexus as well as on the overall nexus. The novel aspects of the methodology include its underpinning by life cycle thinking whereby LCA impacts are assigned to different nexus aspects, depending on their relevance to either food, energy, water or health. Another novel feature is the method for quantifying the overall impact on the nexus and its representation in a “nexus quadrilateral” and “pair-wise nexus triangles” to enable more structured and transparent interpretation of the results. The methodology is generic and can be applied to different systems. Here, its application is demonstrated by considering the impacts on the nexus of recovering resources from food waste within the context of a circular economy. This illustrative example has been chosen due to the importance of food waste for food, water, energy and human health and a lack of quantitative studies on its impacts on the whole nexus. A circular economy context is considered due to the increasing pressures for its implementation in the European Union (EC, 2015) and the need to understand better if “circular” necessarily means “environmentally sustainable”.

2. Methods

This section first outlines the proposed food-energy-water-health (FEWH) nexus methodology, followed by the rationale for assigning different LCA impacts to each nexus aspect in section 2.2. The validation of the method through comparison with multi-criteria decision analysis is discussed in Section 2.3. Finally, the case study used to illustrate the methodology is detailed in Section 2.4.

2.1. The nexus methodology

The LCA impacts assigned to different nexus aspects are first normalised and then aggregated to determine the score for each aspect. To help visualise the overall impact on the nexus, the aspect scores are plotted on a four-sided polygon, with each side representing one of the nexus aspects; this is termed here the “nexus quadrilateral”. The latter is illustrated by a hypothetical example in Fig. 1. The overall nexus impact is then determined by considering all pair-wise interconnections (six in total) between the four nexus aspects and summing up the area covered by the formed pair-wise triangles, as also illustrated in Fig. 1. This is explained in more detail below.

The environmental impacts are normalised for each aspect and option being evaluated as follows:

$$EI'_{n,a} = \frac{EI_{n,a} - EI_{\min,n,a}}{EI_{\max,n,a} - EI_{\min,n,a}} \quad (1)$$

where:

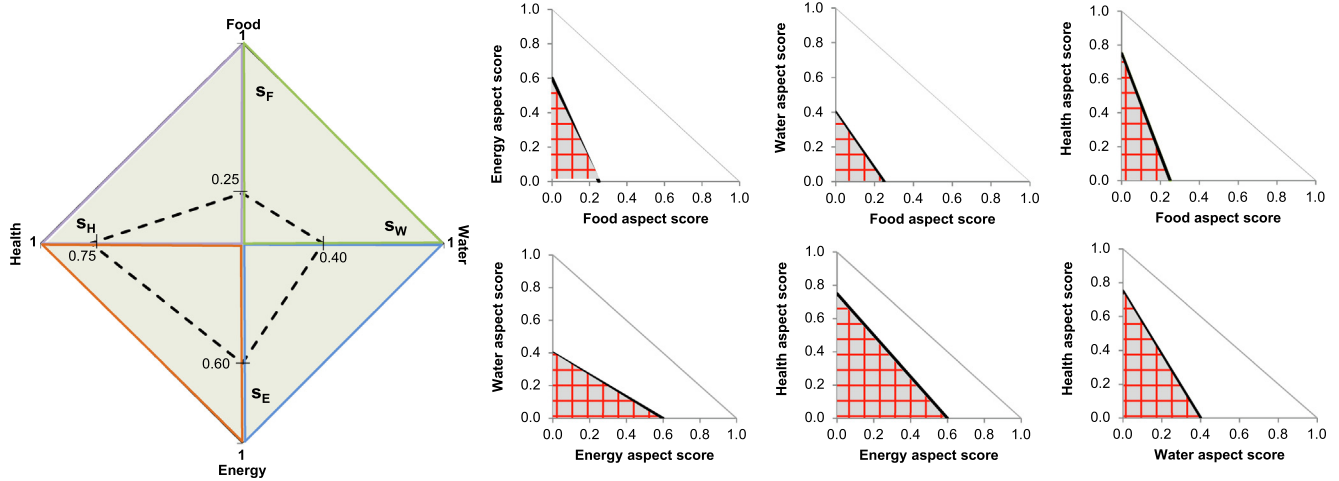


Fig. 1. Illustration of the food-energy-water-health nexus in a quadrilateral (left) and pair-wise interactions in the nexus (right). (Left: The broken line in the nexus quadrilateral illustrates the impact on all four aspects of the nexus simultaneously. Right: Hatched triangles represent impacts on two aspects of the nexus at a time showing the pair-wise interactions. The sum of the hatched triangle areas represents the total impact on the nexus. The larger the total area, the higher the overall impact).

$El'_{n,a}$	normalised LCA impact n assigned to nexus aspect a
$El_{n,a}$	LCA impact n assigned to nexus aspect a
$El_{min,n,a}$	minimum value of LCA impact n assigned to nexus aspect a across options considered
$El_{max,n,a}$	maximum value of LCA impact n assigned to nexus aspect a .

$S_F, S_E, S_W,$	scores for the food, energy, water and health
S_H	aspects, respectively, corresponding to s_a in Eq. (2)
El_{nexus}	total nexus impact.

The normalised impacts range from 0 to 1. They are then aggregated using weights of importance to determine the scores for each aspect according to:

$$s_a = \frac{\sum_{n=1}^N w_n El'_{n,a}}{N} \quad (2)$$

where:

s_a	score for nexus aspects a (food, energy, water or health)
w_n	weighting factor for the normalised impact n assigned to the nexus aspect a , indicating its importance relative to other impacts
N	total number of impacts for aspect a .

The lower the aspect score, the lower the impact on the nexus. The scores can be plotted as the nexus quadrilateral to help visualise their overall impact, as shown in the illustrative example in Fig. 1. If more than one option is evaluated, the nexus quadrilateral can be used to rank them visually in a qualitative way. This is followed by the quantification of their total impact on the nexus by considering pair-wise interconnections among all four aspects, i.e.: food and energy, food and water, food and health, energy and water, energy and health, and water and health. For this purpose, the scores for each pair of the nexus aspects are plotted on (six) graphs to form pair-wise triangles, as illustrated in Fig. 1. The area of each triangle represents the impact on the two aspects forming that triangle. The total impact on the FEWH nexus is then determined as the sum of the areas of the six triangles:

$$El_{nexus} = \left(\frac{S_F S_E}{2} + \frac{S_F S_W}{2} + \frac{S_F S_H}{2} + \frac{S_E S_W}{2} + \frac{S_E S_H}{2} + \frac{S_W S_H}{2} \right) \quad (3)$$

where:

The nexus impact can range from 0 (no impact) to 3 (highest impact). The latter is achieved if all scores for all the nexus aspects are equal to 1. Note that by definition (Eq. (3)), the nexus aspects are considered to be equally important; however, the importance of impacts within each aspect can be changed as indicated in Eq. (2).

Considering the simple example in Fig. 1, the aspect scores presented in the nexus quadrilateral are assumed to be: $s_F = 0.25$, $s_E = 0.60$, $s_W = 0.40$ and $s_H = 0.75$. Plotting these in the six pair-wise graphs and using Eq. (3) yields the total area of 0.71 which then represents the total impact on the nexus.

The following section describes the LCA impact categories considered and how they are assigned to each of the four nexus aspects.

2.2. Assigning environmental impacts to the nexus aspects

In this study, the ReCiPe V1.08 method (Goedkoop et al., 2013) is used to estimate the life cycle environmental impacts in the FEWH nexus. A total of 18 impacts are considered by this method. However, fossil depletion is not included in the nexus analysis to avoid double counting as primary energy demand (PED) is considered instead; the latter is estimated according to the Thinkstep (2019) method included in the GaBi LCA software. Ionising radiation is also omitted as this impact is only directly relevant to nuclear electricity systems. Thus, for the purposes of the illustration of the nexus methodology, which considers different options for food waste treatment, IR is not relevant. However, it can be considered within the health aspect if deemed directly relevant to the system studied.

Therefore, a total of 17 impacts are considered as detailed in Table 1. Out of these, in the base case, six impacts are assigned to the food aspect, one to the energy, five to the water and four to the health. Metal depletion (MD) is not included in the base case as it is not specifically attributable to any of the four aspects, but it is considered as part of a sensitivity analysis. The latter examines the effect of different allocations of the impacts to the nexus aspects through three scenarios defined in Table 1. As can be seen,

Table 1

Life cycle impacts considered in the study and their allocation to different nexus aspects. The LCA impacts of different food waste treatment options used for the illustration of the nexus methodology are also shown.

Environmental impacts	Impacts assigned to different nexus aspects ^a				Waste treatment methods ^b				Unit per tonne of waste treated
	Base case	Scenario 1	Scenario 2	Scenario 3	Anaerobic digestion	In-vessel composting	Incineration	Landfill	
Primary energy demand	E	E	E	E	−1936.03	1310.1	−904.27	136.72	MJ
Global warming potential	F	F	H	H	−31.47	77.51	−5.02	195.49	kg CO ₂ eq.
Metal depletion	–	–	–	E	−1.02	0.73	1.61	0.65	kg Fe eq.
Freshwater ecotoxicity	W	W	W	W	−3.87	1.38	−1.84	−0.18	kg 1,4-DB ^c eq.
Marine ecotoxicity	W	F	F	F	−3.53	1.28	−1.74	−0.23	kg 1,4-DB ^c eq.
Terrestrial ecotoxicity	F	F	F	F	−5.16	3.82	1.16	2.88	g 1,4-DB ^c eq.
Human toxicity	H	H	H	H	−21.55	4.48	−0.23	4.5	kg 1,4-DB ^c eq.
Freshwater eutrophication	W	W	W	W	−11.56	−0.88	4.78	2.8	g P eq.
Marine eutrophication	W	F	F	F	0.72	0.39	0.12	7.43	kg N eq.
Terrestrial acidification	F	F	F	F	7.63	10.13	0.39	0.24	kg SO ₂ eq.
Particulate matter formation	H	H	H	H	1.00	1.38	0.18	0.11	kg PM ₁₀ eq.
Photochemical oxidant formation	H	H	H	H	0.17	0.66	0.85	0.45	kg NMVOC ^d eq.
Ozone depletion	H	H	H	H	−4.57	8.77	0.49	5.36	mg CFC-11 eq.
Agricultural land occupation	F	F	F	F	0.59	4.08	−0.37	0.79	m ² yr
Urban land occupation	F	F	F	F	−0.21	−0.67	0.01	3.85	m ² yr
Natural land transformation	F	F	F	F	0.004	0.011	0.008	−0.036	m ²
Water depletion	W	W	W	W	−273.95	97.07	−149.02	−39.43	m ³

^a F: food; E: energy; W: water; H: human health.

^b Source: [Slorach et al. \(2019\)](#).

^c DB: dichlorobenzene.

^d NMVOC: non-methane volatile organic compounds.

in Scenarios 1, 2 and 3, marine impacts are allocated to the food rather than the water aspect, as marine water quality arguably has a greater impact on seafood stocks than the availability of potable water. Scenarios 2 and 3 assign global warming potential (GWP) to the health aspect to reflect its impact on humans.

2.2.1. Food aspect

The five impacts assigned to the food aspect in the base case are: agricultural land occupation (ALO), urban land occupation (ULO), natural land transformation (NLT), terrestrial ecotoxicity (TET), terrestrial acidification (TA) and GWP. ALO indicates how much land is needed for the cultivation of crops or rearing of animals, much of which is used to supply food. NLT and ULO impact upon the health of ecosystems as habitat loss is a driver for the loss of biodiversity, especially relevant for food production as pollinating insect populations are in sharp decline ([Sánchez-Bayo and Wyckhuys, 2019](#)). Therefore, the importance of biodiversity for resilient and sustainable food agriculture is being increasingly recognised ([Crenna et al., 2019](#); [FAO, 2019](#)).

TET also affects the health of ecosystems by releasing toxic compounds to industrial soil that can harm livestock, soil organisms and reduce biodiversity. Soil acidification arises from the emissions of compounds that contribute to TA. Each crop has a critical soil pH below which bioavailability of nutrients is restricted, which limits plant growth; the acidity can also increase the concentration of aluminium in soil to a level toxic to plants ([Goulding, 2016](#)).

GWP is expected to affect food production through rising temperatures and extreme weather events. For example, while increased temperatures and rising CO₂ concentrations may improve agricultural yields in high latitudes, global production of wheat, maize, soybean and rice are all projected to fall with a rise in temperature ([Hoegh-Guldberg et al., 2018](#)). Extreme weather events, such as droughts and flooding, will increase stresses on crops and on livestock ([IPCC, 2012](#)). There is also a high risk to mid- and low-latitude fisheries and fish stocks with temperatures

increasing by 1.5 °C; this includes the acidification of the oceans ([Hoegh-Guldberg et al., 2018](#)). In addition to the base case, GWP is also assigned to the food aspect in Scenario 1, while in the remaining two scenarios, it is assigned to the health aspect as discussed in Section 2.2.4.

2.2.2. Energy

The only impact directly relevant to the energy aspect is PED and so it is assigned to this aspect in the base case and all the three scenarios considered in the sensitivity analysis.

In addition to PED, MD is considered in Scenario 3 for this aspect to reflect the fact that the energy sector and, particularly, many renewable electricity technologies are reliant on common and rare metals ([Fizaine and Court, 2015](#)).

2.2.3. Water

The impacts that affect aquatic ecosystems are assigned to the water aspect of the nexus. Water depletion (WD) quantifies the amount of water used in the life cycle of the system of interest and is a simple measure of the impact on the security of water supply. The run-off of nutrients into waterways and the resulting freshwater eutrophication (FE) lead to increased growth of auto-trophic species which block the sunlight and deplete dissolved oxygen; this ultimately leads to a reduction in aquatic biodiversity. Similarly, freshwater ecotoxicity (FET) poses a risk to the whole ecosystem but can also affect directly the supply of potable water for human consumption.

There are analogous impacts for the marine environment through marine eutrophication (ME) and marine ecotoxicity (MET). Therefore, these are also assigned to the water nexus aspect in the base case. However, as mentioned earlier, they are considered as part of the food aspect in Scenarios 1–3.

2.2.4. Human health

The impacts that can affect human health are human toxicity (HT), particulate matter formation (PMF), photochemical oxidant

formation (POF) and ozone depletion (OD). HT captures the potential harm of substances released to air, including carcinogens. Respiratory and cardiovascular diseases have both been shown to be exacerbated and caused by PMF in the air, which is also attributed to causing impaired infant lung development (Kim et al., 2015). POF or “summer smog”, and particularly tropospheric ozone, has also been shown to reduce lung function, exacerbate respiratory conditions, such as asthma, and cause long term tissue damage (Amann, 2008). Finally, OD increases the level of solar UV-B radiation on the earth, which has the potential to increase the incidences of skin cancers, genetic damage and macular degeneration; increased UV-B radiation also has the benefit of increasing vitamin D levels in humans (Norval et al., 2011).

Therefore, these impacts have been assigned to the health aspect in the base case and all other scenarios (Table 1). In addition, GWP is assigned to this aspect in Scenarios 2 and 3. This is due to climate change endangering human health through the increased occurrence of extreme weather events, such as heat waves, droughts and hurricanes, and by changing the distribution of allergens and infectious diseases (Franchini and Mannucci, 2015).

2.3. The nexus methodology and multi-criteria decision analysis

An alternative method for estimating the total environmental impact within the FEWH nexus would be to use one of the multi-criteria decision analysis (MCDA) methods instead. To explore how the proposed nexus method compares to MCDA and whether the results of the illustrative case study differ between the two, multi-attribute value theory (Azapagic and Perdan, 2005b) has been used in this study. As an illustration, only the base case is considered, with the same allocation of the impacts in the MCDA as in the nexus methodology; this is illustrated in the decision tree in Fig. 2.

The scores for the four aspects are weighted and summed up to determine an overall nexus impact as follows:

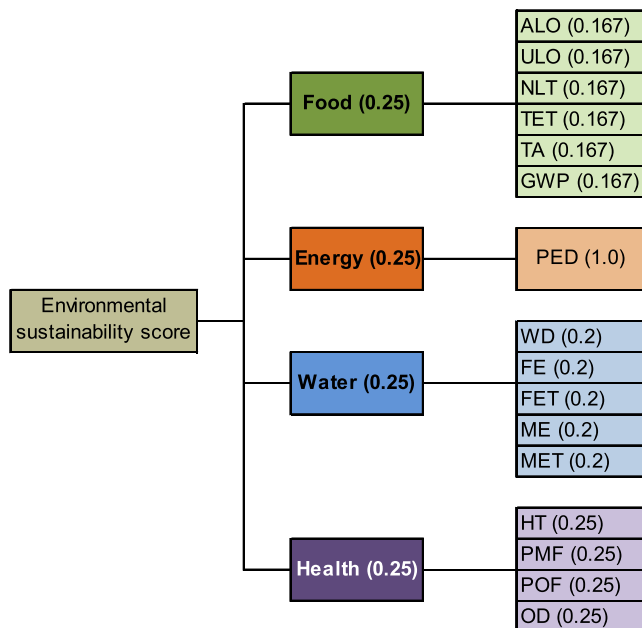


Fig. 2. MCDA decision tree for the four aspects of the FEWH nexus. (The allocation of the impacts to the different nexus aspects is the same as in the base case for the nexus methodology (see Table 1). The values in brackets represent the weights assumed for the aspects and the impacts, based on equal importance of each. For the impacts acronyms, see Nomenclature).

$$EI_{\text{nexus}} = \sum_{a=1}^A s_a \quad (4)$$

In this case, the nexus impact can range from 0 (the lowest) to 1 (highest). Note that, in congruence with the nexus methodology, all the aspects are assumed to have equal importance.

The aspect scores are estimated according to:

$$s_a = \sum_{n=1}^N w_n EI'_{n,a} \quad (5)$$

where the normalised LCA impact $EI'_{n,a}$ allocated to aspect a is estimated using Eq. (1).

2.4. Illustrative case study: recovery of resources from food waste

To illustrate the nexus methodology, the case study considers the life cycle environmental impact on the FEWH nexus of four options for food waste management used widely in the European Union (Manfredi and Pant, 2011), each of which recovers energy and/or material resources: anaerobic digestion (AD), in-vessel composting (IVC), incineration and landfilling. The functional unit is defined as the “treatment of 1 tonne of household food waste” and the system boundaries are given in Fig. 3. The study is based in the UK. A brief description of the waste treatment methods is given below; for the original LCA results and further details, see Slorach et al. (2019).

Anaerobic digestion: AD of food waste takes place at a commercial facility with an annual capacity of 25,000 t/yr. The produced biogas is burned on-site in a combined heat and power engine with the excess electricity exported to the grid for which the system is credited. The digestate is used in agriculture, with the credits for displacing an equivalent amount of mineral fertiliser.

In-vessel composting: A rotating drum is used to manage the composting of food waste at a 50,000 t/yr facility. The facility has a controlled atmosphere with scrubbers to limit air emissions and odours. The waste is retained in the drums for four days before being matured in open air windrows. The compost is applied in agriculture and the system is credited for displacing mineral fertilisers.

Incineration: The incineration process takes place in a large scale facility (300,000 t/yr) using a moving grate furnace, where the food waste is embedded in general municipal solid waste. The heat in combustion gases is used to produce steam, which drives a turbine to generate electricity; the process is credited for displacing the grid electricity. The flue gases are treated before release to the atmosphere, including removal of fly ash, which is sent to landfill together with bottom ashes.

Landfilling: A modern sanitary landfill is considered with a contained system to capture landfill gas (68% capture rate) and collect leachate for wastewater treatment. A gas engine is used to generate electricity from the gas for exporting to the grid; the system is credited for displacing the equivalent grid electricity.

The LCA impacts of these options were estimated previously by Slorach et al. (2019) using the ReCiPe V1.08 methodology. These are summarised in Table 1, together with their allocations to the different nexus aspects (as discussed in Section 2.2).

3. Results and discussion

3.1. Overall impact on the nexus

The impacts on the nexus of the four food waste treatment options, estimated using Eqs. (1)–(3), are illustrated in the nexus quadrilaterals in Fig. 4 for the base case and Scenarios 1–3, with the total nexus impacts summarised in Table S1 in the Supplementary Information (SI). For the full details of the estimations, see Table S2 and Figures S1–S4 in the SI. In all the cases, it is assumed

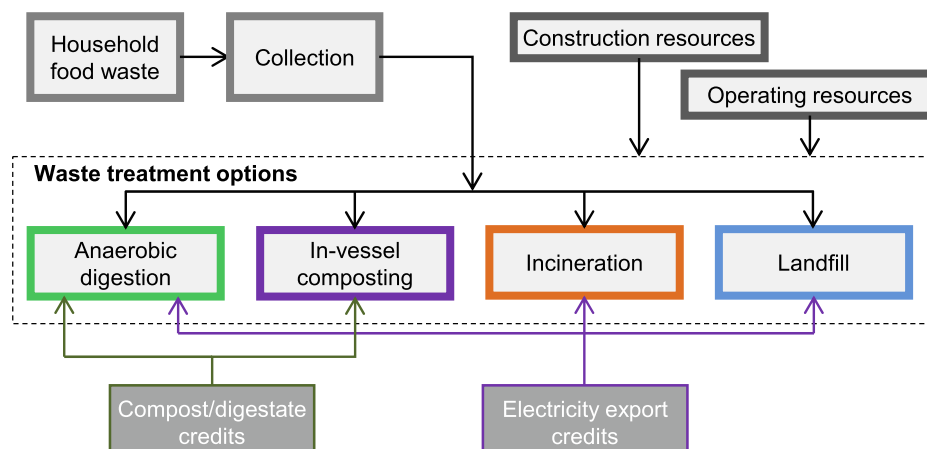


Fig. 3. Food waste treatment options and the system boundaries considered in the case study (adapted from Slorach et al. (2019)).

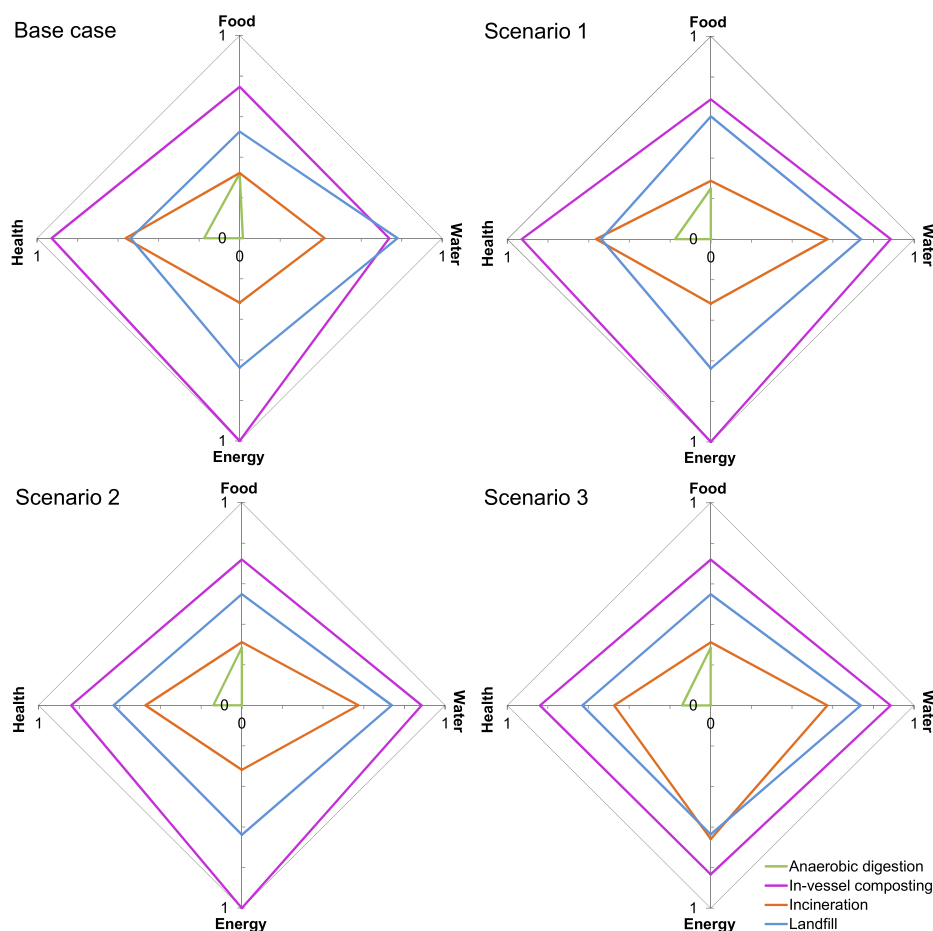


Fig. 4. Impact of the food waste treatment options on the food-energy-water-health nexus for the base case and Scenarios 1–3, assuming equal importance of all nexus aspects and the impacts.

that all the impacts and nexus aspects have equal importance, with the weights for each provided in Fig. 2.

As can be seen from Fig. 4 and in Table S1, AD has the lowest nexus impact of 0.032 in the base case. Considering the individual nexus aspects, it also has the lowest impact on energy, water and health, predominantly due to displacing the largest amount of electricity and requiring fewer resources for operation. Incineration is the next best option but with the overall nexus impact (0.48) 15 times higher than for AD. It has a slightly higher impact

on the food aspect than AD and the second highest on the health aspect, close to that of landfilling. The impact of incineration on health is due to the air pollution (POF and PMF) caused by the flue gas emissions. Landfilling has the highest impact on water and a total nexus impact of 1.15, which is 36 times greater than that of AD. One of the key influencing factors is the leachate management, which has a high contribution to marine eutrophication. IVC is the worst option overall, with the nexus impact (2.17), almost double that of landfill. It also has the greatest impact on the food, energy

and health aspects. Therefore, these results show that circularity does not necessarily lead to environmental sustainability, particularly as IVC is favoured over incineration and landfilling within a circular economy context (EMF, 2015).

When ME and MET are assigned to the food aspect in Scenario 1, there is limited change to the nexus impacts and no change in the ranking of the treatment options (Table S1 in the SI). In this case, the AD impact goes down by 32% (from 0.032 to 0.022) due to two reasons: the food aspect has the greatest influence on the AD nexus impact and AD has the lowest MET. The scores of all other options increase only slightly (~5%). A similar trend is found for Scenario 2, where GWP is assigned to health instead of food.

However, a slightly different trend can be noticed for Scenario 3 where MD is assigned to the energy aspect. The greatest change in the nexus impacts is for incineration which increases by 54% on the base case. This is related to the construction and operation of the incineration plant which requires more material resources and hence has a higher MD than the other treatment options. Owing to its lower MD, IVC sees its nexus impact drop to 2.01 from 2.17 in the base case.

Therefore, these findings demonstrate that the results obtained through the proposed nexus methodology are robust with respect to the allocation of impacts to different nexus aspects, with no change in the ranking of the options considered. However, this may not be the case for other systems and the sensitivity to the allocation of impacts should be explored.

3.2. Nexus interconnections

This section discusses the pair-wise interconnections between the four nexus aspects to demonstrate further the nexus methodology and illustrate how the quantitative results (see Figs. A1–A4) can be combined with qualitative analyses.

3.2.1. Food-energy interconnections

AD and incineration are both net producers of energy through exporting electricity to the grid. However, when considering use of this energy for food production, the contribution would be relatively small: 9% for AD and 4% for incineration. This is based on the PED for food production in the EU of 20.2 GJ/t of food (Monforti-Ferrario et al., 2015) and the PED values for AD and incineration of –1.9 and –0.9 GJ/t of food waste, respectively (Slorach et al., 2019). Although utilising food waste as a renewable energy source is recommended within a circular economy (Ellen MacArthur Foundation, 2013), this is energetically much less efficient than waste prevention.

3.2.2. Food-water interconnections

AD digestate can contain approximately 95% water (Rigby and Smith, 2011). When applied to the soil, this water is used to grow crops, but it does not form a significant fraction of water used in agriculture and much of the water is added during treatment. However, the application of both the AD digestate and IVC compost are associated with ammonia volatilisation and nitrate run-off, which results in ME. However, the run-off and treatment of leachate from landfills lead to ten times greater ME than that of AD and therefore poses a greater threat to the health and biodiversity of coastal regions. Incineration has very low ME, but is the greatest contributor to FE due to the leaching of phosphorus from the fly ash (DEFRA, 2011). FE has a direct impact on the quality of water available for crop irrigation and drinking. This is particularly relevant in developing countries where removing nutrients from water has a high cost (Reddy et al., 2018). Both FE and ME are mainly related to the electricity used and/or credited across the treatments.

3.2.3. Food-health interconnections

Compost and digestate are generally considered beneficial for soil quality as they supply key plant nutrients and avoid the use of synthetic fertilisers. This can improve the sustainability of food supply and reduce the intensive production of fertilisers which can be harmful to human health (Sutton et al., 2013). It has been suggested that the long-term use of compost can sequester carbon in soils (Favoio and Hogg, 2008) which could help abate carbon dioxide emissions. However, the long-term use of digestate derived from livestock slurry has been linked to an accumulation of metals in the soil, which could be detrimental to plant growth (Nkoa, 2014). On the other hand, food-derived digestate has generally been shown to have significantly lower levels of heavy metals (Rigby and Smith, 2011).

The maturation of compost and the application of digestate result in ammonia volatilisation to the air. Ammonia binds with other pollutants to form fine particulate matter which increases mortality rates (WHO, 2018b). Furthermore, despite flue gas treatment, incineration still releases some nitrogen oxides and non-methane volatile organic compounds to the air. This results in incineration having the highest potential to cause summer smog (through POF), which can trigger asthma, reduce lung function and cause lung diseases (WHO, 2018b).

3.2.4. Energy-water interconnections

The main influence of the waste treatment options on water use is associated with the grid electricity displaced. Therefore, AD has the lowest water depletion as it generates the highest amount of electricity. None of the routes is a significant primary user of water.

3.2.5. Energy-health interconnections

Electricity used in IVC and emissions from landfilling are the main contributors to human toxicity and related impacts on human health. Both AD and incineration have a net-negative HT, thus avoiding the related impacts on health by displacing the equivalent amount of grid electricity.

3.2.6. Water-health interconnections

As discussed in Section 3.2.2, eutrophication impacts on the quality of freshwater and the necessity for treatment. Likewise, FET and MET affect the biodiversity of aquatic life and potentially water supply security, depending on the water treatment infrastructure. None of the waste treatment routes has a significant direct contribution to FET or MET and the impacts are again driven by electricity.

3.3. Sensitivity analysis: Weighting of impacts

The above results are predicated on equal weighting of impacts and could change if the importance of some impacts was greater than of others. This section explores if the outcomes of the study change with the weighting of impacts. Two cases are evaluated: the first considers grouping of similar impacts and then weighting them equally and the second explores the change in the importance of individual impacts needed to incur a change in the ranking of options.

3.3.1. Weighting groups of similar impacts

Weighted groupings avoid implicit bias if there are two or more similar impacts. For example, ALO, ULO and NLT all represent a form of land use change and weighting each separately effectively assigns a greater weight to land use (as in the base case). To address this, while still assuming equal weighting of all impacts, each of the three impacts is assigned the weight of 0.33. This means that land use as a whole has a weighting of 1. A similar approach is used for the impacts related to terrestrial, marine

and freshwater environments as shown in Table 2. Therefore, no impact is given priority within each nexus aspect. For example, in the water aspect, the two freshwater impacts (FET and FE) have a total weighting of 1, as do the two marine impacts (MET and ME), alongside water depletion which is also weighted at 1.

As indicated in Fig. 5, the group-weighting has a negligible effect on the nexus impacts of the treatment options, with marginal deviation from the base case. Nevertheless, group-weighting is recommended when applying the nexus methodology to avoid potential implicit bias towards some impacts.

3.3.2. Change in weighting needed to change the ranking of options

Table S3 in the SI presents the change in importance and the related weighting of each impact needed to change the ranking of options in different nexus aspects relative to the base case. The greatest increase in importance is needed for ME (26 times) and POF (seven times). This changes the ranking of incineration in the water and health aspects, respectively. Therefore, quite significant changes in the importance (and weighting) are needed despite incineration having the lowest impact for ME and the highest for POF.

The relative change in the importance of the rest of impacts needed to change the ranking of options ranges between 0.9 (TET) and four times (GWP and PMF). For example, increasing the importance of PMF four-fold results in both landfilling and incineration having a lower impact on the health aspect than AD. This is due to the high PMF of AD. For similar reasons, doubling the importance of TA leads to a higher impact of AD on the food aspect than of incineration. The only impact for which the importance has to be decreased (0.9) to change the ranking of options is TET.

However, none of the changes in the importance of the impacts shown in Table S3 has any significant effect on the total nexus impacts and the overall ranking of the options remains the same as in the base case.

3.4. Comparison of the nexus methodology and MCDA

The results of the MCDA estimated by Eq. (4) and (5) are summarised in Fig. 6 for the base case and Scenarios 1–3. As in the nexus methodology, all impacts and aspects are assumed to have equal importance, using the weights in Fig. 2.

Although the total nexus impacts are different between the nexus methodology and the MCDA, the ranking of the options remains the same for all the cases considered. However, there are some differences in the relative distances between the options. For example, the nexus impact of IVC is 68 times higher than that of AD, while the equivalent difference in MCDA is 6.5 times. In general, there is consistently a lower relative difference between the treatment options in MCDA compared to the nexus methodology, but this does not affect their overall ranking.

The weighting applied to the individual aspects could potentially change the overall sustainability rankings. However, as indicated in Table S4 in the SI, the ranking of the options in the food,

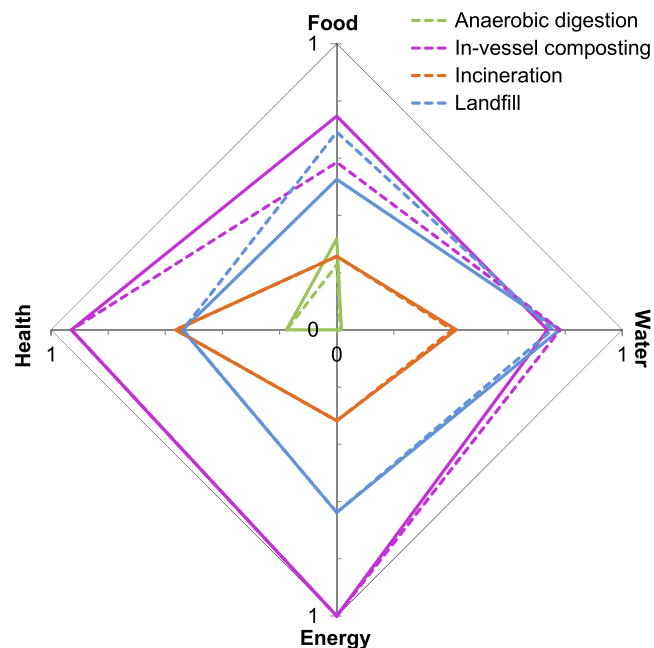


Fig. 5. The effect on the nexus impacts of grouping and weighting similar impacts. [The solid lines refer to the base case and the broken lines to the group-weighting].

energy and health aspects matches that of the overall ranking so changing the weighting would not lead to a change in ranking of the treatment options. The only change is found if the importance of the water aspect is increased by a factor of 24. In that case, landfilling overtakes IVC as the third best option, but this weighting effectively eliminates the effects of the other aspects.

Therefore, these results demonstrate that the outcomes obtained through the proposed nexus methodology are in good agreement with the MCDA outcomes for this particular case study. Although this serves to validate the methodology, it is also possible that the outcomes between the two could be quite different for other systems. Further exploration of this is recommended for future work.

3.5. Limitations and application of the nexus methodology

The proposed nexus methodology provides a framework in which the environmental impacts of different systems can be interpreted within a FEWH nexus. It can therefore guide assessments and comparisons of products, technologies and human activities in a more structured and systematic way.

However, the methodology has several limitations. First, as it is underpinned by LCA, it is reliant on the availability of LCA studies of the systems of interest. It also requires estimates on a number of LCA impacts to cover all four nexus aspects. Therefore, this method should be seen as an extension of LCA, rather than stand-alone.

Furthermore, some impacts are cross-cutting and are difficult to assign to one aspect. This limitation can be addressed through a

Table 2
Grouping and weighting of similar impacts.

Impact category ^a	PED	GWP	FET ^b	FE ^b	MET ^c	ME ^c	TET ^d	TA ^d	HT	PMF	POF	OD	ALO ^e	ULO ^e	NLT ^e	WD
Weighting	1	1	0.5	0.5	0.5	0.5	0.5	0.5	1	1	1	1	0.33	0.33	0.33	1
Nexus aspect	E	F	F	F	W	W	F	F	H	H	H	H	F	F	F	W

^a For impacts acronym, see Nomenclature.

^b Freshwater impacts.

^c Marine impacts.

^d Terrestrial impacts.

^e Land-related impacts.

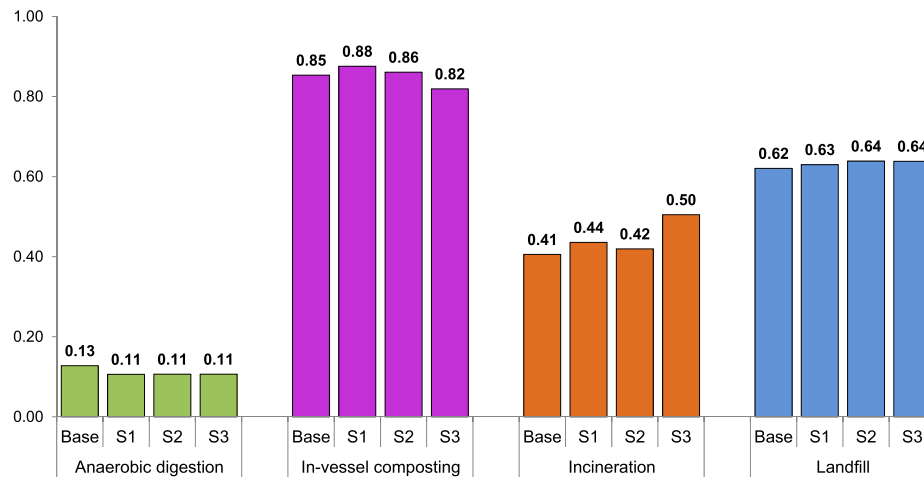


Fig. 6. Overall impact on the nexus of the food waste treatment options estimated through MCDA for the base case and Scenarios 1–3. (The lower the score, the better the option).

sensitivity analysis, as demonstrated in this work. Another limitation is that the estimation requires subjective grouping and weightings of LCA impacts. This is also the limitation of the valuation stage in LCA as well as MCDA and can be dealt with through sensitivity analyses to explore the effect of different weights on the outcomes of the analysis.

A further limitation of the proposed methodology is that all four aspects are considered to have the same importance, while in MCDA, for example, it is possible to change the aspects' weights. However, the methodology allows for different weighting of the impacts within each aspect. These could be obtained by eliciting preferences of relevant stakeholders (Azapagic and Perdan, 2005a) or applying a range of objective weighting functions (OECD-JRC, 2008).

The example in this paper is limited to LCA impacts and thus environmental sustainability. The methodology can be broadened to consider economic and social sustainability by including related indicators. Quantitative indicators can be normalised and included within the appropriate nexus aspect alongside LCA impacts. Qualitative issues could either be converted into quantitative measures using an appropriate technique (as commonly done in MCDA) or could be discussed qualitatively as part of wider nexus interconnections.

4. Conclusions and recommendations

This paper has proposed a new method for quantifying environmental impacts on the food-energy-water-health nexus. The methodology is underpinned by life cycle thinking and uses LCA impacts to estimate the overall impact on the nexus. The LCA impacts can be allocated to different aspects and aggregated using weighting factors, based on stakeholder interests and preferences. The method is generic and can be applied to any product, process or human activity to assess its environmental sustainability within the nexus. It also allows for exploration of the interconnections between different aspects of the nexus.

The methodology has been illustrated by considering the impacts on the nexus of recovering resources from food waste within the context of a circular economy. The findings show that anaerobic digestion has the lowest impacts on all four nexus aspects and the lowest overall nexus impact (0.032). Anaerobic digestion primarily impacts the nexus through ammonia emissions from digestate, which affects the food aspect through terrestrial acidification and the health aspect through particulate matter formation. Despite having a similar impact on the food aspect, the

nexus impact for incineration (0.48) is 15 times greater than that of anaerobic digestion. Incineration has a marginally greater impact on health than landfill due to the air pollution from flue gases. However, the overall nexus impact for landfilling (1.15) is more than double that of incineration. Owing to high marine eutrophication related to the leachate, landfilling also has the highest impact on the water aspect. In-vessel composting is the worst option overall (2.17), with the nexus impact 68 times higher than anaerobic digestion. It also has the highest impact on the food, energy and health aspects as it is a net consumer of grid electricity. The ranking of the options does not change by allocating the impacts to different nexus aspects. Similarly, changing the weighting of the impacts has no effect on the ranking, although the impacts on the individual nexus aspects change to a certain extent. The comparison of the results with those obtained via multi-criteria decision analysis shows that the ranking outcomes are robust for the systems considered.

Therefore, the methodology can be used to strengthen the findings of an LCA study or provide further insights into the environmental sustainability of different systems that may not be evident from LCA impacts alone. For example, in this particular case, consideration of the nexus and the interactions between its different aspects reinforced the LCA findings that anaerobic digestion is the best option and in-vessel composting the worst, also showing that 'circular' does not necessarily mean 'environmentally sustainable'. However, depending on the systems considered, the findings of the LCA and the nexus methodology may not always be aligned in which case the latter can be used to provide deeper understanding of the interactions of different impacts within the nexus. It is thus recommended that future work applies the methodology to other systems. It may be possible to add other aspects to the four considered here, such as waste and resources. Broadening the methodology to include two other sustainability dimensions – economic and social – is also recommended. Development of tools for nexus estimations would also be valuable.

Declaration of Competing Interest

The authors declare no conflict of interest.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.wasman.2020.06.012>.

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