A multi-criteria sustainability assessment framework: development and application in comparing two food waste management options using a UK region as a case study

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Abstract

Preventing food wastage is a key element of sustainable resource management. But as food waste is still generated at high volumes, priority is placed on its proper management as a resource, maximising sustainability benefits. This study, by integrating a multi-criteria decision analysis with a sustainability assessment approach, develops a screening and decision support framework for comparing the sustainability performance of food waste management options. A structured process for selecting criteria based on the consideration of environmental, economic and social aspects related to region-specific food waste system planning, policy and management has been developed. Two food waste management options, namely the use of food waste disposal units, which grind food waste at the household's kitchen sink and discharge it to the sewer, and the anaerobic co-digestion of separately collected food waste with sewage sludge, were selected for comparison due to their potential to create synergies between local authorities, waste and water companies, with local circumstances determining which of the two options to adopt. A simplified process used for assessing and comparing the two food waste management options in the Anglian region in the UK, indicated that there are benefits in using the framework as a screening tool for identifying which option may be the most sustainable. To support decision-making, a detailed analysis that incorporates stakeholders' perspectives is required. An additional use of the framework can be in providing recommendations for optimising food waste management options in a specific region, maximising their sustainability performance.

Keywords: Food waste, food waste disposal units (FWDs), anaerobic co-digestion, sustainability assessment framework, multi-criteria analysis, decision-making

1. Introduction

Ten million tonnes of food waste (i.e. raw or cooked food materials discarded before, during or after meal preparation in the household, and in the post-farm-gate, manufacture, distribution, retail, wholesale and hospitality and food service sectors) are estimated to be produced each year in the UK, 60% of which could have been avoided (WRAP 2016). Despite considerable developments at the post-farm-gate and manufacture sectors, and households, which have led to a combined reduction of approximately 2 million tonnes of food waste in 2015 compared to the production levels of 2007, progress in reducing food waste arisings in the UK remains slow (WRAP 2016). Modelling suggests that without any further interventions, food waste may increase by 1.1 million tonnes by 2025 (WRAP 2016).

A number of alternatives such as incineration (Inaba et al. 2010; Khoo et al. 2010), composting (Cerda et al. 2018; Li et al. 2013) and anaerobic digestion (Andreottola et al. 2012; Capson-Tojo et al. 2016; Ragazzi et al. 2017) are currently available for the treatment of food waste, while surplus food redistribution is also gaining attention (Facchini et al. 2017). Incineration and composting are considered to be the least desirable food waste management options from a sustainability perspective (Paritosh et al. 2017) as the high moisture content and variability in the type and amount of municipal food waste arisings can be a hindrance to their successful and efficient performance (Iacovidou et al. 2012b). Anaerobic digestion, despite its prominent place in policy making as a sustainable energy alternative, is also considered to be a challenging option, due to the variability of food waste that causes instability in the performance of the process. Two other less widespread alternatives used for the management of food waste are the use of food waste disposal units (FWDs), and the anaerobic co-digestion of separately collected food waste with sewage sludge (Hidaka et al. 2015; Wang et al. 2017; Wickham et al. 2016). The FWD is an electric device placed under the household sink that grinds food waste at source and discharges it through a water outlet to the sewer for subsequent treatment at wastewater treatment plants (WWTPs). The anaerobic co-digestion process involves the digestion of two substrates together as a way to improve digestion efficiency and increase the energy output. It is a well-established process in Europe (Iacovidou et al. 2012b). These alternatives are seriously considered by the water industry sector as a way to retain the value in food waste and maximise its recovery.

Nonetheless, the current debate on the: i) impacts of the use of FWDs on water consumption, sewerage system and the WWTPs; ii) value exploitation potential of food waste and effectiveness of the food waste collection schemes; and iii) feasibility of co-digesting food waste with sewage sludge, has made decision-making for local authorities (LAs) and the water industry a challenging task. This is because the sustainability potential of the two food waste management options depends largely on the area-specific characteristics, household practices, condition of the sewer system and type of treatment at the receiving WWTP, amongst other factors. A sustainability tool for assessing and comparing the two options based on their environmental, economic and social impacts is required (Iacovidou et al. 2012a; Iacovidou et al. 2012b; Iacovidou et al. 2012c).

Sustainability assessment is increasingly used in the decision making and policy development areas. It offers new perspectives to impact assessment and integrates scientific- and policy-based research in order to produce solutions based on a transdisciplinary approach that takes into account (and potentially involves) all stakeholder requirements (Sala et al. 2015). As the varying options available for food waste management can perform differently in terms of sustainability across the environmental, economic and social pillars, a robust assessment framework that supports multifaceted decision-making in the selection of the most sustainable management practice is considered to be key.

Of the various decision tools that are currently available, multi-criteria analysis (MCA) is considered to be one of the most appropriate methods, and which has been extensively used for sustainability assessment processes (Cinelli et al. 2014; Milutinović et al. 2014). This is because MCA has the ability to account and evaluate multiple dimensions of impacts, based on an explicit set of criteria, in a way that facilitates comparison of a range of alternatives in a simple manner (Angelo et al. 2017; Balasubramaniam and Voulvoulis 2005; Kiker et al. 2005). MCA is an evaluation and decision support approach that is frequently applied to compare and assess the impact of different policies and waste management options (Achillas et al. 2013; Keeney and Raiffa 1993; Kiddee et al. 2013). It is suitable in addressing complex problems featuring high uncertainty, conflicting objectives, using different forms of data and information, while acknowledging diverse interests and perspectives, and the complexity of the evolving biophysical and socio-economic systems (Balasubramaniam and Voulvoulis 2005; Boggia and Cortina 2010; Ferrarini et al. 2001; Garfì et al. 2009).

In this study, by integrating the principles of MCA with sustainability assessment considerations (Ashley et al. 2008; Gudmundsson et al. 2016), a screening and decision support framework is developed to assess and compare the sustainability performance of food waste management options based on area-specific characteristics. Using the Anglian water region in the UK as a case study, the framework developed is used for the comparison of the use of FWDs and the anaerobic co-digestion of food waste with sewage sludge in terms of their sustainability performance, and findings on the potential of the framework to support the selection of the most sustainable food waste management option are presented. Then, the key outcomes of the study are discussed, before drawing some concluding remarks.

2. The sustainability assessment framework

The key objective of our sustainability assessment framework (SAF) is to compare the performance of food waste management options in terms of sustainability (Fig. 1). This, as suggested by others, necessitates a clear understanding of what the scope, scale and focus of the assessment is (Cinelli et al. 2014; Iacovidou et al. 2017b), in order to enable the development of a robust framework that would streamline the assessment process. The initial step of the SAF is to specify the geographical scope and scale (e.g. local, regional or national level) of the system under assessment and clearly define the system's boundaries. Then, the food waste management alternatives are identified, pertained to the specific context set by the stakeholders (Fig. 1). Measuring sustainability of the selected food waste management alternatives, requires a carefully selected set of criteria. In our framework, reflecting sustainability, environmental, social and economic criteria are identified (Fig. 1), each of which is composed by a set of sub-criteria.

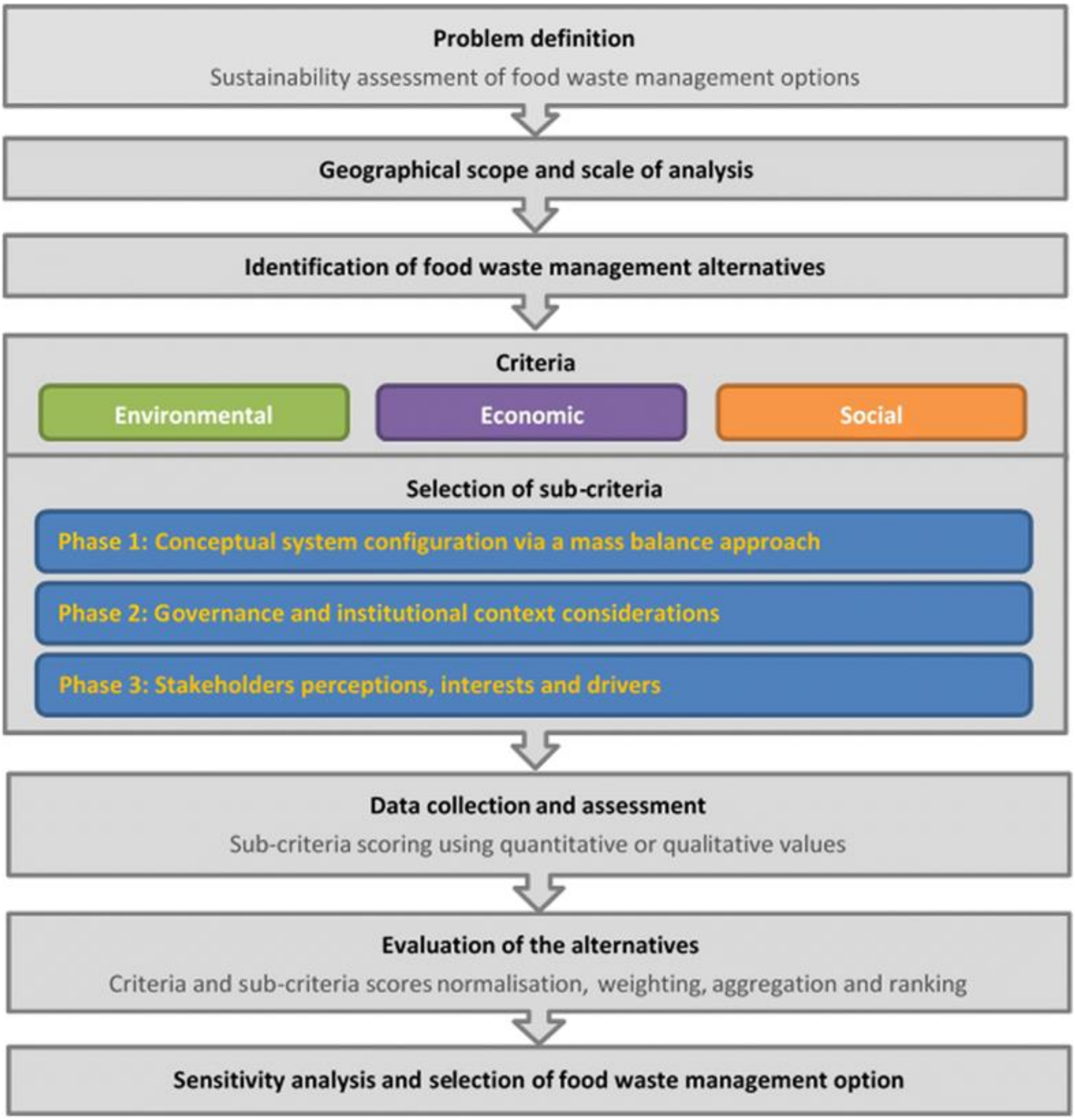

Fig. 1
Sustainability decision-making framework using multi-criteria approach to evaluation of the problem

The selection of sub-criteria is highly dependent to the extent at which stakeholders can explicitly incorporate sustainability considerations into their decision-making process (based on their requirements, interests and motives) (Ashley et al. 2008; Cabot et al. 2009), and their ability to select sub-criteria that enable a comprehensive and meaningful sustainability assessment of food waste management options (Milutinović et al. 2014). A rigorous and transparent sub-criteria selection process can increase the scientific credibility of the sustainability assessment framework (SAF) and allow for a proper conceptual understanding of the system and of the key considerations associated with each key criterion (e.g. environmental, economic and social), which is essential for good policy making. In this study, as shown in Fig. 1, the identification of sub-criteria is guided by three clearly outlined phases: (1) the mass balance configuration, (2) the governance and institutional context (e.g. policies and other socio-economic drivers) assessment, and (3) stakeholders' values. The latter phase is often considered to be the most important in guiding the selection of key sub-criteria for assessing the sustainability of the two food waste management options, but we regard this as a subjective and intuitive way of sub-criteria selection when is used in itself. In our perspective, an understanding of the system dynamics based on geo-spatial practices, institutional setting, economic and social drivers, legislation enforcement, financial mechanisms, infrastructure availability and social behaviour and cultural aspects is critical in guiding sub-criteria selection. Based on that, we consider phases 1 and 2 to be sufficient in guiding sub-criteria selection when using the framework as a screening tool, and phase 3 is used when a more detailed, holistic analysis is needed, as it can reinforce sub-criteria selection and stipulate aspects that would otherwise be overlooked.

Following the selection of the sub-criteria, the quantitative and qualitative data collection and assessment is performed. An evaluation matrix that contains the estimates (scores) of each sub-criterion used in the assessment of the food waste management alternatives is created. Then, both the criteria and sub-criteria are normalised and evaluated using weights, which indicate the relative contribution and importance of each criterion/sub-criterion in the evaluation process. Weights are numerical scores on a scale extending from 0 to 100, where 0 represents the lowest relative importance, and 100 is associated with the highest relative importance. Based on their aggregated weights, the food waste management alternatives are finally ranked. There are various MCA methods that could be employed to perform the criteria/sub-criteria weighting, aggregation and ranking, e.g. elementary process (Wang et al. 2009); MAVT, multi attribute value theory (Kiker et al. 2005); AHP, analytical hierarchy process (Milutinović et al. 2014); ELECTRE, elimination and choice expressing the reality (Hokkanen and Salminen 1997; Karagiannidis and Moussiopoulos 1997); PROMETHEE, preference ranking organisation method for enrichment of evaluations (Rousis et al. 2008); selection of the most appropriate method must be consistent with decision-makers' needs (Rowley et al. 2012). Exploration on which MCA method is the most robust is beyond the scope of this study, and relevant information can be found elsewhere (Achillas et al. 2013; Cinelli et al. 2014; Mendoza and Martins 2006; Wang et al. 2009).

After the evaluation of the alternatives, a sensitivity and uncertainty analysis of the weights of criteria/sub-criteria is performed for facilitating an insightful selection of the best performing process across all criteria/sub-criteria.

2.1. Pool of sub-criteria used in food waste management systems assessment

An important component of the SAF is the selection of sub-criteria that would streamline the sustainability assessment of the food waste management alternatives. In our study, this list was compiled by critically examining the scientific literature to determine which environmental, economic and social aspects of food waste management systems were reportedly the most effective at capturing aspects associated with food waste management systems, and at improving their performance. Aspects pertained to life cycle assessment (LCA) and life cycle costing (LCC) of food waste management, food waste system planning, food waste policy, food waste technologies used and sustainability assessment of food waste management systems relevant to region-specific characteristics and stakeholder preferences were considered.

Presented across the three sustainability pillars (i.e. environmental, economic and social), the criteria identified are summarised in Table 1.

Table 1 Typical (sub-) criteria used in food waste management systems assessment

Criterion	Sub-criteria	References
Environmental	*Non-energy (abiotic) resource consumption (e.g. water, minerals, etc.)*	[1-4,14]
	Energy resource consumption	[2-11,14]
	Global warming potential (or else known as greenhouse gas emissions, GHG)(Direct)	[1-6,8-12]
	Indirect carbon emissions	[7,10]
	Human toxicity potential (HTP)	[1, 4, 5, 10, 12,14]
	Photochemical ozone formation potential (POFP)	[1, 3, 5, 6, 10, 11]
	Acidification potential	[1-6, 9-12]
	Eutrophication potential	[1-6, 10-12]
	Ozone depletion potential	[2, 3, 5, 9, 10]

	Ecotoxicity potential	[4, 5, 12]
	Land use	[1]
	Diversion of organic waste fraction from landfilling	[1,13]
	Chemical fertilisers/peat substitution	[2-4, 6, 13]
	Renewable energy generation	[3, 6, 7, 12,13]
Economic	*Cost of raw materials and intermediates*	[1, 9, 14]
	Capital costs (e.g. land, equipment, etc.)	[1, 4, 9,14]
	Operational and maintenance costs (e.g. depreciation costs of trucks, repair fees, license tax, inspection fee; labour cost, such as wage, retirement pay; insurance cost of industrial disaster, health, annuity, etc.)	[1, 4, 9, 14]
	Net profit/loss (e.g. net sales from goods sold, general and administrative expenses, amortization and adjustment of intangible assets, income tax, etc.)	[14]
	Utilities cost (e.g. energy and water services, discharge of end products)	[4, 9]
	Revenue from secondary resource sale	[1, 9]
	Subsidy and incentives (e.g. carbon credit offset)	[9,13]
Social	*Social acceptability (e.g. of the FWM alternative)*	[1,14]
	Social equity (e.g. equitable distribution of benefits from the FWM to citizens)	[1]
	Odours (e.g. nuisance caused by the FWM alternative)	[1]
	Noise (e.g. caused by the FWM alternative)	[1]
	Job creation (e.g. due to implementation of the FWM alternative)	[1]
	Employment quality (e.g. during each stage of FWM alternative)	[1]

FWM: Food waste management; Sources: [1] (den Boer et al. 2007); [2] (Bernstad and la Cour Jansen 2011); [3] (Righi et al. 2013); [4] (Lundie and Peters 2005); [5] (Saer et al. 2013); [6] (Khoo et al. 2010); [7] (Inaba et al. 2010); [8] (Kim and Kim 2010); [9] (Kim et al. 2011); [10] (Sonesson et al. 2000); [11] (Padeyanda et al. 2016); [12] (Lee et al. 2007); [13] (Levis et al. 2010); [14] (Hung et al. 2007)

FWM food waste management

Measuring the sustainability of food waste management systems is a complex task. Although selection and use of a large number of sub-criteria is perceived to be the only way of capturing the fundamental aspects of each food waste management option assessed, it can make it difficult to evaluate their sustainability in a comprehensive manner (Diaz-Balteiro et al. 2017). Besides sub-criteria from the three sustainability pillars, technical aspects such as technologies used and their maturity state, as well as their reliability, efficiency and resilience over time, and non-technical ones such as regulatory framework and policy measures, must also be included in the analysis (Bernstad and la Cour Jansen 2011; Iacovidou et al. 2017b). The following section demonstrates the applicability of the framework in assessing the performance of the two food waste management alternatives in the Anglian water region in the UK.

3. Application of SAF to evaluate the performance of the use of FWDs and anaerobic co-digestion of food waste with sewage sludge in the Anglian water region

Constraints in holding the participatory approach as a prerequisite of Phase 3: stakeholders' perceptions, interests and drivers, meant that the framework developed in this study was used as a screening tool. As a result, a good understanding of the region-specific characteristics was considered to be key. To evaluate the sustainability performance of the use of FWDs and the anaerobic co-digestion of separately collected food waste with sewage sludge, the following considerations were made:
Geographical scope and scale: the Anglian water region in the UK was used as a case study because of the good understanding of the issues pertained to this region gained from the authors' previous work (Iacovidou et al. 2012a, 2012b, 2012c). This region is one of the areas with the fastest growing population in the UK. According to the Environment Agency, it is also one of the driest regions with an average of 600 mm of rainfall each year, in contrast to the average 900 mm for the rest of England and Wales (Anglian Water Services Ltd. 2017). Anglian Water is the largest water and wastewater treatment provider in England and Wales covering 20% of the land area (27,476 km2) and provides services to 22 local authorities (LAs) (county and unitary) (Anglian Water Services Ltd. 2017).

Identification of alternatives: the use of FWDs and the anaerobic co-digestion of separately collected food waste with sewage sludge, as defined in the "Introduction" section.

Selection of sub-criteria: conceptualisation of the food waste flow from source to final treatment and disposal was performed for each of the alternatives as a prerequisite of Phase 1 of the sub-criteria selection process of the framework. This is illustrated in Fig. 2. Conceptual configurations enable a better understanding of the steps and processes involved in a food waste management system, and the implications of those in the sustainability of the entire system.

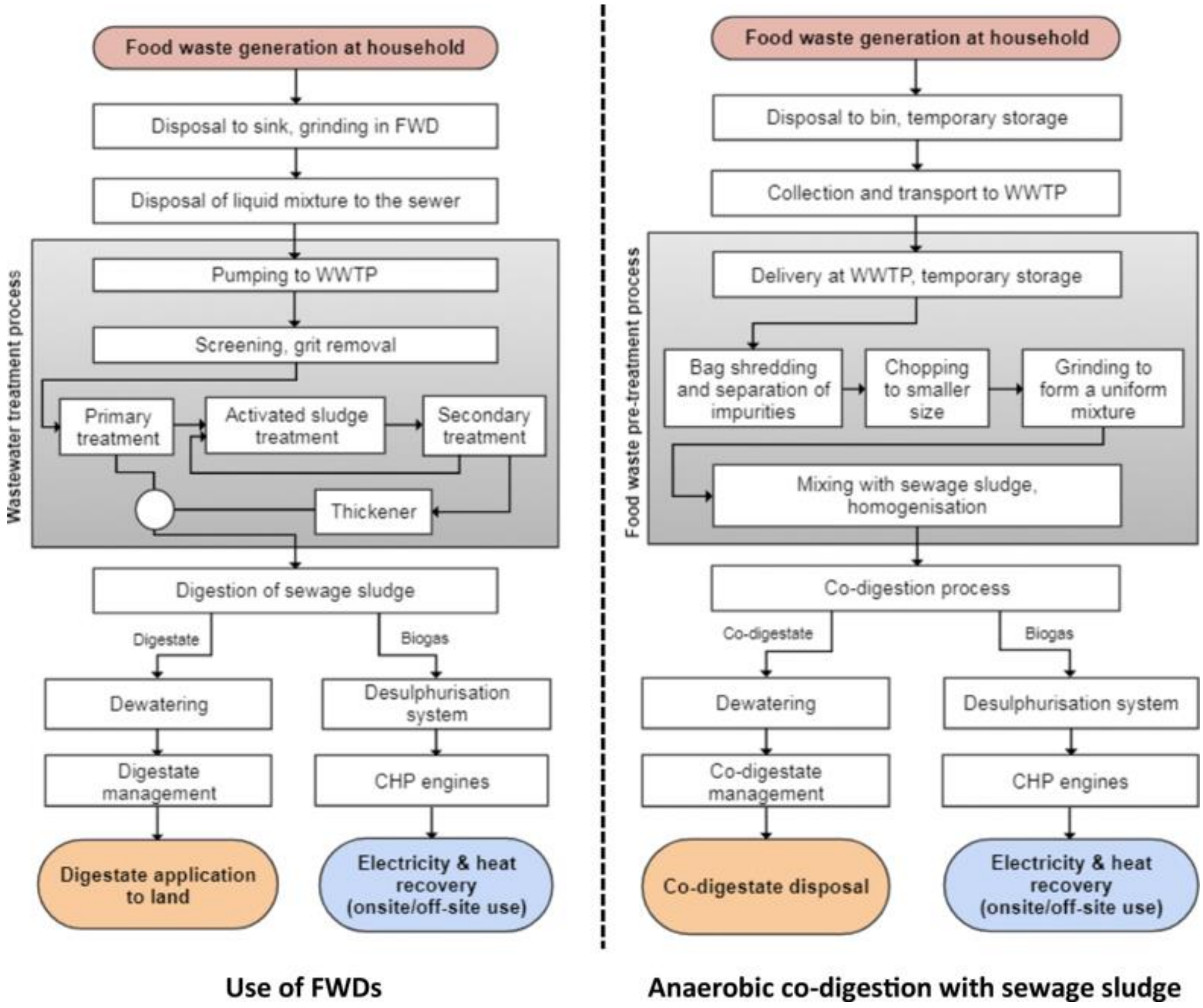

Fig. 2 Conceptual configuration of the food waste flow in each of the two food waste management alternatives

In Phase 2, we reflected on the governance and institutional considerations associated with both options. Legislations such as the EU Landfill Directive (1999/31/EC) and the revised EU Waste Framework Directive (2008/98/EC) currently mandate the UK, to not only divert biodegradable waste, such as food waste, from landfill, but to promote food waste prevention, reuse and recycling (European Parliament and Council 2008; European Union 1999). As a result, the UK government has commited to diverting food waste from landfill and increasing renewable energy generation, which are considered to be key drivers in increasing the uptake of the use of FWDs and the anaerobic co-digestion with sewage sludge for the treatment of food waste (DECC and Defra 2011). For a robust distribution of impacts when assessing the sustainability performance of the two food waste management options in the Anglian region (as well as in any region in the UK), systemic factors associated with population and/or number of households served (and the number of occupants per household) by each option in the region, the amount of food waste managed by each option compared to the amount generated in the region, and the potential need for additional food waste management options due to each technology's penetration/use rate, are important attributes that must be taken into account. Moreover, the ratio of households served by the same water company for both the water supply (which is needed for the use of FWDs) and sewage treatment (where grinded food waste ends up) is particularly important in assessing the sustainability performance of the use of FWDs. In the case of anaerobic co-digestion of food waste with sewage sludge, the composition of the food waste produced in the region, and of the sewage sludge produced at the WWTP, are key features that need to be considered for ensuring the feasibility of the co-digestion process in the first place; whilst, the ability of the 22 LAs served by the Anglian Water industry to provide separate food waste collection schemes and the identification of the WWTPs at which the co-digestion process could be implemented are additional aspects that a sound decision-making analysis should include. These systemic aspects can influence the outcome of the comparison between food waste management options. In this study, a simplified approach was used in comparing the two food waste management options, and many of these challenges have not been taken into account.

The degree at which environmental permitting regulations, landfill tax and financial incentives can affect the prevalence of the one option over the other in the Anglian region was considered. Anaerobic co-digestion of food waste with sewage sludge is controlled under the environmental permitting regulations to ensure (i) the use of resulting biogas, and the storage and spreading of co-digestate to land is attained in a way that is safe to the environment and human health, and (ii) the size of the combined heat and power (CHP) plants is appropriately scaled when wastes other than sewage sludge would be added to the water company's anaerobic digesters. This, together with the need to comply with the Animal By-Products Regulations that require food waste to be pasteurised or sterilised before and/or after the anaerobic co-digestion process, and the end-of-waste (EoW) criteria certification for digestate, present additional challenges to the water industry. These challenges can be partly compensated by the financial incentives provided from renewable energy generation and the dilution of some potentially toxic compounds such as heavy and light metal ions and organic compounds found in sewage sludge, which can make the digestate produced of higher value. The carbon credits attained by the industry and the potential gate fees applied could also be considered additional benefits of the co-digestion alternative.

The use of FWDs is regarded a more flexible solution as it is used as a household appliance, and no regulations are currently in place to control its installation rate. At household level, implications with the use of FWDs can be associated to blockage of pipes often due to their size and configuration, and to materials caught in the FWD unit; evidence of such blockages are limited in the literature. The most pronounced implications of FWDs are those associated with sewer blockages due to fat, oil and grease (FOG) deposition of food waste particles, and the increase in water consumption and wastewater generation; both of which imply increased pressures to LAs and the water industry. An increase in the wastewater generation would require additional costs due to an increase in the intensity of wastewater treatment processes for the removal of the additional organic load and substances up to the stringent requirements set by the Water Framework Directive (WFD). A high penetration rate of FWDs would also require the water industry to cater for changes in the capacity of WWTPs, and the seasonality of the organic load they receive for treatment, as a result of changes in the amount and type of food waste produced and on tourism patterns.

The anaerobic co-digestion of food waste with sewage sludge is a solution of which viability and sustainability depends largely on the separate collection and segregation of food waste at source. Impurities found in food waste, such as plastics, metals, glass and other packaging parts are likely to cause tremendous technical problems in the wastewater treatment line and co-digestion performance (Iacovidou et al. 2012b). This adds pressure on LAs that may have to make provisions for raising awareness on the quality of the food waste collected from household and catering establishments. The waste contractor responsible for the separate collection of food waste on behalf of the LAs in the Anglian Water region will have to make provisions for the right infrastructure (e.g. truck fleet, personnel, licences) to be put in place. Separate collection of food waste by LAs can be regarded as an opportunity to increase job creation which is amongst the top priorities of the UK government's agenda. However, food waste prevention and redistribution initiatives can bring the investment in the anaerobic co-digestion of food waste with sewage sludge, as well as the benefits accruing from it (e.g., job creation, separate collection infrastructure, etc.), at risk for both the waste and water industry. Thus, considerations on feedstock availability over the investment's lifetime and potential depreciation plans will have to be put in place.

Uncertainty due to inadequate legislative frameworks and limited institutional capacity, coupled with governance instabilities due to political reforms, must also be accounted over the lifetime of each option in order to gauge how these potential changes might affect their long-term sustainability. For a robust sustainability assessment process, attention must also be given on the lifetime of the equipment used, as well as on the end-of-life (EoL) management of each technology. While anaerobic digestion has a lifetime of around 20–25 years (Gebrezgabher et al. 2010), FWD units have a lifetime of approximately 10–12 years (Diggelman and Ham 2003; InSinkErator 2011) and their replacement costs and other impacts (e.g. non-energy resource consumption, energy resource consumption, etc.) would have to be accounted in order to be comparable with the digester's lifetime. Although technological advances have increased the life expectancy of FWDs, their EoL management fate is currently unknown. Durability and EoL considerations of the equipment used for the pre-treatment, digestion and post-treatment of food waste are important to be included in the analysis, yet information on these aspects is still lacking.

The core environmental, economic and social sub-criteria for assessing the sustainability of the two options were narrowed down, as described below.

- Environmental sub-criteria include non-energy resource consumption, energy resource consumption and GHG emissions (direct and indirect) produced at the acquisition (e.g. manufacturing, transporting and installing), use and EoL management of FWDs, and during the treatment of the increased strength wastewater at WWTP, which may vary depending on the technical configuration of the WWTP, operating conditions and available capacity. In regards to the latter, it was reported that the use of FWDs cause little change in the additional loadings to the WWTP and thus capacity may not be an issue (Iacovidou et al. 2012a). In the case of anaerobic co-digestion of food waste with sewage sludge, energy and non-energy resource consumption and GHG emissions must be accounted during the separate collection, transportation, construction of a food waste mechanical pre-treatment facility (e.g. mechanical, thermal, chemical, and biological prior to anaerobic co-digestion), co-digestion and post-treatment, including biogas cleaning/scrubbing processes and transportation and disposal/use of digestate (Møller et al. 2009). The latter may vary based on the type of digester used and the distribution/utilisation routes and marketability of the end products. Fugitive losses from the anaerobic reactor and utilisation of the biogas produced through the combined heat and power (CHP) engines, as well as land use due to the construction of food waste pre-treatment facility at the WWTP, need also to be included in the assessment. Land requirements for the construction of the food waste pre-treatment and storage facilities for the digestate produced can create a negative impact to the surrounding environment. However, the degree of this impact may vary depending on the area-specific characteristics, and the technologies adopted, as some technologies require less space than others. Anaerobic co-digestion's GHG emissions can be offset by renewable energy generation (via biogas production) and partly from chemical fertiliser substitution due to the use of the digestate produced, although the degree to which the latter is used in the UK is currently constraint by the lack of a coherent regulatory framework in regard to certifying its quality status (Iacovidou et al. 2012b). Both alternatives are reported to contribute minimally to acidification, ozone depletion potential, photochemical ozone formation potential and ecotoxicity, although some nitrous oxide (NOx) emissions via manufacturing processes, combustion of the biogas in the combined heat and power (CHP) engines and emissions from digestate storage have been reported (Iacovidou et al.

2017a; Sonesson et al. 2000; Whiting and Azapagic 2014). The eutrophication potential may prevail due to the risk of nutrient leaching to surface and ground water from the wastewater effluents and or digestate application to land (Di Maria and Micale 2015). Risks to human health from the storage and decomposition of food waste in the household may occur via the inhalation of substances such as volatile organic compounds (VOCs) (e.g. methane thiol, MeSH; hydrogen sulphide, H2S), sulphur compounds, amines and aromatic hydrocarbons, which can cause nausea, bronchitis and gastrointestinal problems (Defra 2007a). Risks to human health may also result through the animal by-products present in food waste, although pasteurisation prior to digestion with sewage sludge is sought to be employed to ensure destruction of communicable diseases such as spongiform encephalopathy and foot and mouth disease, and weed seeds, reducing the need for herbicide use (Lukehurst et al. 2010). In the case of FWDs, regular cleaning and maintenance of the unit is reported to prevent fouling and disease spread.

- Economic sub-criteria include costs associated with the acquisition, operation and maintenance/replacement costs of the unit; sewer cleansing and maintenance associated with increased fat, oil, and grease (FOG) related to food waste flow to the WWTP and additional capital, operational and utility costs associated with the treatment of increased organic load in WWTP (e.g. capacity, aeration and nutrient control measures) (Iacovidou et al. 2012a). In the anaerobic co-digestion of food waste with sewage sludge, caddies/bins, vehicles and labour costs associated with the separate collection and transportation of food waste, alongside capital (e.g. planning, land, process equipment and set-up), operational/maintenance costs (e.g. pre-treatment costs for food waste preparation, digestion costs, post-treatment costs associated with biogas cleaning/scrubbing processes, feeding into the national gas grid or storing and digestate preliminary post-treatment and enhancement) and utility costs need to be accounted. Biogas that is used on site, or is cleaned and exported to the grid, may be eligible for a number of financial incentives which vary depending on the type of technologies used and the capacity of the anaerobic digestion plant. When biogas is used on site, it can replace grid-supplied heat and/or electricity, thus reducing associated utility costs. Biogas that is used to generate electricity/heat and exported to the grid is eligible for revenues (e.g. Renewable Obligation Certificates, ROCs; Renewable Heat Incentives, RHIs) and financial incentives for alleviating global warming impacts (e.g. Levy Exemption certificates, LEC). Carbon credits for avoided GHG emissions are debatable in regard to their ownership; thus, discussion of this is outside the scope of this study. In the case of the use of FWDs, significant savings can be achieved from fossil fuel reduction in the collection and transport of food waste (den Boer et al. 2007; Iacovidou et al. 2013).

Digestate that fails to meet the EoW criteria is still regarded as a waste, and additional costs are incurred for its disposal.

- Social sub-criteria include social–cultural considerations towards the adoption of a new food waste handling concept at household (e.g. assurance in using the FWDs technology) or separation of food waste at source, which shows the degree of acceptance of each food waste practice (Balkema et al. 2002). The use of FWDs was reported to be associated with some opposition, as a number of people found their use annoying due to noise implications, or laziness (Evans 2007), but technological advancement of the units has enhanced their adaptability. In the anaerobic co-digestion of food waste with sewage sludge, attitudes and issues around source-separation of food waste at source depends on personal health and hygiene standards in the household, sensitivity and cultural and social background (Defra 2007b). Health and safety of the staff involved in each food waste management option is another important consideration, as they can be exposed to high level of volatile organic compounds (VOCs), sulphur compounds, amines and aromatic hydrocarbons emissions during the collection and pre-treatment of food waste, or its disposal into the sewer and its thereafter cleaning and maintenance (Evans 2007). The storage of food waste in households and its subsequent collection and handling can be associated with odour implications (CECED 2003). Food waste grinding into the FWDs has not been reported to release any kind of unpleasant odours, though food waste disposed into the sewer has the possibility of producing some. The anaerobic degradation of food waste particles in the sewer may however lead to the production of H2S even at very low concentrations (Iacovidou et al. 2012a). Noise associated with the use of FWDs inside households can be of a greater magnitude as opposed to those coming from the outside and can be a limiting factor to the use of each alternative (Evans 2007). Job creation can be associated with an increase in staff responsible for the installation and maintenance of FWDs, whereas in the anaerobic co-digestion process, staff for the collection, transportation and pre-treatment is needed.

Following the above, the sub-criteria selected from assessing the performance of the two food waste management alternatives under each criterion are presented in Fig. 3.

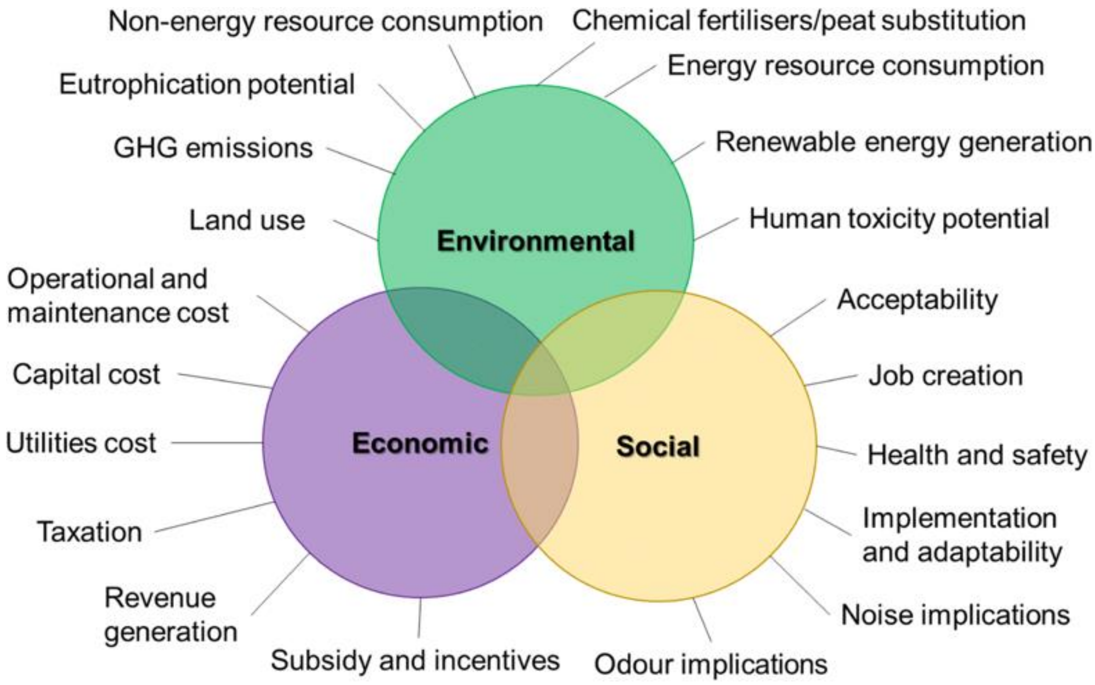

Fig. 3 Selected sub-criteria for the sustainability assessment of the use of FWDs and the anaerobic co-digestion of food waste with sewage sludge in the Anglian water region in the UK

Due to data availability and time constraints at the time of the study, only a few of the identified sub-criteria were included in the analysis. More specifically, in the environmental criterion, we looked at the non-energy and energy resource consumption, which were grouped together into 'net resource consumption', the GHG emissions and the renewable energy generation; in the economic criterion, we accounted the 'net costs' (i.e. aggregate of capital, operational and maintenance, and utility costs) and revenues; and in the social criterion, the acceptability of the food waste management option, health and safety, odour and noise implications (den Boer et al. 2007).

Data collection and assessment

In order to assess the two food waste management options against the sub-criteria selected for the analysis, data from Anglian Water services reports, and reports regarding the use of FWDs and the collection of food waste from LAs in the Anglian region, were collected and used. When these were not available, data based on UK figures were adopted from the scientific literature. Qualitative scores were measured on a plus scale of two degrees of measurement (+/++), with + being used for the process with the least positive response and ++ for the process with the higher positive response. Details on data collected and the way this were processed are summarised in Supplementary Material.

The overall assessment was performed based on a tonne of food waste grinded/collected and managed. The scoring of the alternatives against the selected sub-criteria is presented in the evaluation matrix (San Cristobal 2012), shown in Table 2.

Table 2 Evaluation matrix of the two food waste management options used in the case study

Criteria	Sub-criteria	Unit (per tonne FW)	FWDs	Anaerobic co-digestion
Environmental	Net resource consumption	kWh	188.34	265.71
	GHG emissions	$kgCO_2$	99.26	84.27
	Renewable energy generation	kWh	668.64	2173.08
Economic	Net costs	£	68.47	192.97
	Revenues	£	66.86	217.31
Social	Acceptability	+/++	+	++
	Health & safety	+/++	++	+
	Odour implications	+/++	++	+
	Noise implications	+/++	+	++

Note: Negative values indicate savings/net benefits

Evaluation of the alternatives

To evaluate the performance of the two food waste management alternatives based on the scores presented in Table 2, the DEFINITE (ver. 3.0) decision support software was employed (Janssen and van Herwijnen 1994). With this software, it was possible to evaluate the performance of criteria/sub-criteria using a range of analytical methods, while it was also possible to carry out uncertainty and sensitivity analyses related to variations in the criteria/sub-criteria weightings (Chon et al. 2012). In this study, we used the elementary MCA analysis based on the weighted summation method. Weighted summation is a well-established and widely used method, detailed information on which can be found in Janssen (2001).

The sub-criteria used in the analysis are measured in different units and scales. As such, for the ranking of the alternatives to be performed, the scores of the sub-criteria need to be transformed into comparable values. To achieve that, a process called standardisation or normalisation is employed, where the sub-criteria scores lose their dimension and measurement unit and attain a uniform, non-dimensional value (van Herwijnen 2005). In the weighted summation method, a linear function between the lowest and the highest score of a sub-criterion between the alternatives compared is often used to standardise scores. Hence, the scores are transformed according to their relative position on the interval between the lowest and highest score [min, max] and to their relative position on the interval [0, 1]

(Janssen 2001). This analysis in our study was conducted through DEFINITE, and the alternatives were then evaluated via weighting assignment (Janssen and van Herwijnen 1994).

In the weighted summation method, the weights are usually assigned to the criteria/sub-criteria using the equal weight or the rank-order weight methods. Because of the lack of information regarding stakeholders' priorities and interests, and considering that environmental, economic and social criteria and their sub-criteria in a sustainability assessment should be of equal importance, we used the equal weights method as proposed in other studies (Balasubramaniam and Voulvoulis 2005; Gasparatos 2010; van den Hove 2006). Using this method, the sum of the weights of criteria and the partial contribution of the sub-criteria to each criterion should be equal to 1 (or 100%). The standardised score of each criterion/sub-criterion is multiplied by its assigned weight, and a matrix of criteria/sub-criteria scores expressed as ratios is generated (Table S2, Supplementary Material). The ranking of each food waste management alternative is then determined based on a linear additive model (i.e. weighted sum of standardised scores) (Angelis and Kanavos 2017; Boggia and Cortina 2010). The final result is the scoring of the alternatives between 0 and 1, with the highest score representing the best net benefit and thus better sustainability performance (Cinelli et al. 2014). According to this process, the score of the anaerobic co-digestion of food waste with sewage sludge is 0.54, indicating that it could be a more sustainable option than the use of FWDs in the Anglian water region which has scored 0.48 (Fig. 4).

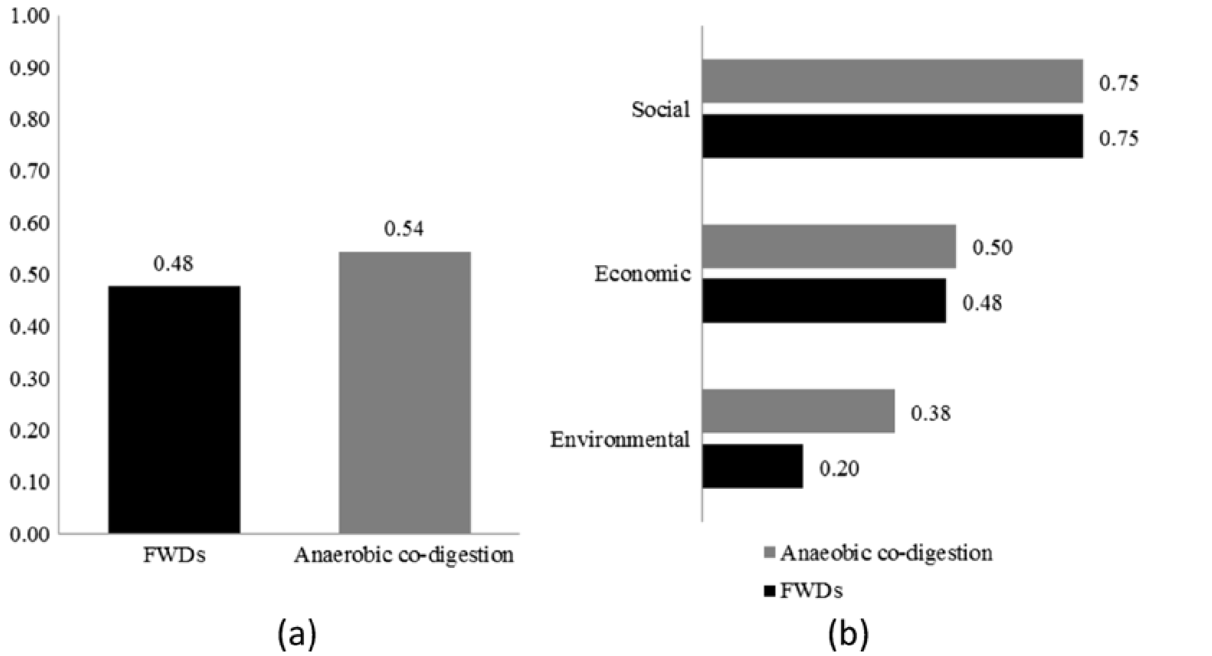

Fig. 4 a Overall score of the evaluation of the two food waste management alternatives with the highest score indicating a better sustainability performance. b Criterion-specific scores of the two food waste management alternatives. The higher the score, the better the sustainability performance of the food waste management option against the respective criterion

Sensitivity analysis

The difference between the overall score of the two food waste management options is very small, and a sensitivity analysis was carried out to look at which sub-criteria could have reversed the sustainability performance of the two food waste management alternatives. This analysis was carried out by changing the weights for the sub-criteria scores on food waste management assessment options within a deviation of ± 50% from the initial ones. This was used as a way to reflect the response of the alternatives to the relative importance of the sub-criteria to the criteria, and identify the sub-criteria which could result in a ranking reversal, using a stochastic method based on a Monte Carlo approach (Boggia and Cortina 2010; Bottero et al. 2011). This analysis was carried out via DEFINITE and helped to gain a better understanding of the impact of these variations on the overall comparison (Boggia and Cortina 2010).

The sub-criteria of net resource consumption, net costs and odour implications and health and safety impacts were the most sensitive to changes in their importance (weights) and could cause a reversal in the ranking of the alternatives, with the use of FWDs becoming more preferable to the anaerobic co-digestion of food waste with sewage sludge. This emphasises that a major component of the developed framework lies on the subjectivity of assessing the contribution of the sub-criteria to the selected criteria, as changes in the relative importance of some sub-criteria could really change the outcome of the analysis.

Discussion

A comparison between the use of FWDs and the anaerobic co-digestion of separately collected food waste with sewage sludge in the Anglian water region in the UK, was performed using the framework developed in this study as a screening tool due to the lack of stakeholders participation. As a result, our analysis could not be used to support decision-making. Nonetheless, it highlighted that the different characteristics of each option and their prevalence in the selected region are important in identifying and understanding the potential sustainability outcomes of their short-, medium- and long-term implementation. Some underlying important outcomes also aroused from the analysis. These are as follows:

Food waste management presents an opportunity for recovering value when properly managed. This value may vary from one treatment process to another; for example, biogas and digestate can be produced from the anaerobic co-digestion of food waste with sewage sludge, but an improved wastewater treatment process due to increased organic load can be achieved when FWDs are used. Notwithstanding these benefits, investigation into which solution may result in the best possible overall outcome is important, and must be properly assessed in pursuing sustainability. Yet, it is evident that creating a water-energy-food nexus generates opportunities for increased resource efficiency, building the foundations of a greener and more sustainable future.

In sustainability assessment processes, consideration of the environmental, economic and social impacts based on the area-specific characteristics (this may include national, regional or local boundaries) and practices are key to the selection of the sub-criteria used in assessing the performance of food waste management alternatives. This process can help to uncover economically feasible and socially acceptable practices, along with key environmental considerations that need to be taken into account to ensure protection of the environment and human health in a concerted manner, such that consideration of the one pillar does not undermine the importance of the other. Challenges related to the selection and implementation of the most sustainable food waste management alternative will continue to exist as a result of increasing population, urbanisation, ageing infrastructure and technological development. As such, stakeholders involved in decision-making processes must be ready to adapt to the changing circumstances and be able to include options that may now seem far-fetching (e.g. surplus food redistribution and avoidable food waste reduction), and select the sub-criteria that can properly address the situation at hand.

Stakeholders' perceptions, interests and drivers are important prerequisites in supporting a sound decision-making process. A participatory approach that requires all stakeholders, which affect and are affected by the implementation of a food waste management option, to be involved in the selection of sub-criteria and the overall decision-making process is fundamental in using the sustainability assessment framework up to its full potential. This participatory process may trigger controversies between different stakeholders (as a result of opposing interests and business objectives), but will also uncover important aspects that must be taken into account when selecting a food waste management option that could become mainstream. Such transparent methods of reflection, deliberation and selection of sub-criteria, and their potential importance to the overall evaluation process by the stakeholders involved, are yet to be developed.

Taking into account the relationship between water provision, energy security and resource efficiency, and implications both in terms of availability and demand, water and environmental challenges often prove complex to address. Nonetheless, these links provide the potential to convey beneficial synergies for the water industry and LAs, or the contractors operating on their behalf, which could deliver real benefits and cross-sectorial solutions, if carefully applied.

Although the SAF presented in this study was designed for food waste management options assessment, its generic approach in grasping systemic challenges means that it may be possible for it to be extended to other waste systems, such as municipal solid wastes, construction and demolition wastes or commercial and industrial waste. A frequent review of the framework, and expansion on some of the key aspects included in the process, would make it a user-friendly tool and enable its uptake by various stakeholders.

Conclusions

Food waste is a valuable resource that can be turned into an opportunity, if the area-specific characteristics and practices implemented for its treatment are taken into account. This is the basic principle that underpins the sustainability assessment framework (SAF) developed in this study, which can be effectively used as a screening as well as an analytical tool for supporting decision-making regarding the selection of a food waste management option based on case-specific contexts. An important component of the SAF is the sub-criteria selection process, which emphasises that the conceptualisation of the food waste flows, the governance, institutional, and socio-cultural aspects that define food waste management systems, as well as the stakeholders' perspectives are critical in streamlining the selection of useful sub-criteria and their evaluation, yielding a comprehensive view of the food waste management system.

The use of FWDs and the anaerobic co-digestion of food waste with sewage sludge are important precedents in demonstrating the applicability of the SAF as they are considered to be two of the most powerful options in recovering value from food waste. This is partly because they can create synergies between the LAs, waste and water industries enabling sustainable food waste management in the long run. In this study, a number of systemic simplifications associated with both options were made for demonstrating the applicability of the SAF, and as such, conclusions on the selection of the one food waste management option over the other could not be rationalised—yet the framework was successfully used in comparing the two options.

Data availability was found to be a major challenge associated with the robustness of the framework. Data is important in getting a holistic perspective of the potential positive and negative impacts of the food waste management alternatives. Hence, lack and inconsistency in the data used may substantially limit the assessment process, and create gaps in understanding the potential effects of adopting the one alternative over the other. Another challenge is related to changes in the national and regional planning and policy, institutional reforms, population increase and urbanisation, socio-technical aspects, economic drivers, ageing infrastructure and technological development all of which would have implications on the practices implemented by LAs, the water and the waste industry. These changes may cause instability in the system and alter stakeholders' preferences and agendas. Thus, in assessing the sustainability of a food waste management option, these aspects must be taken into account together with the specificities of the region, in order to enable the selection of the process that can better support the efficient management of resources in the long-term.

Flexibility is highly required in using the SAF, so that data availability and systemic changes can be properly accounted for, to allow the unequivocal identification of the best food waste management alternative, thereby supporting informed decision-making. For flexibility to be embedded in the framework, further research is required. The environmental, economic, social aspects may need to be expanded to include institutional and technical aspects, utilising both top-down (national-specific) and bottom-up (area-specific) approaches for formulating relevant sub-criteria.

Resource efficiency, and food waste management in particular, is a multi-faceted problem, requiring different kinds of mechanisms and strategies for it to be solved. The framework developed in this study is only but a piece of the puzzle that may allow us to move a bit closer in promoting sustainable waste management solutions.

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Supplementary Material

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A multi-criteria sustainability assessment framework: Development and application in comparing two food waste management options using a UK region as a case study

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Here we present supporting information to the main paper, detailing the methodology followed for the collection of data for the assessing the performance of the use of FWDs and subsequent treatment at the wastewater treatment plant (WWTP), and the anaerobic co-digestion of separately collected food waste with sewage sludge at WWTP, in the Anglian water region in the UK (Section 1); and the criteria assignment procedure (Section 2) and sensitivity analysis outcomes (Section 3).

Section 1: Calculating the performance of both food waste management

Due to data availability and time constraints of the study it was only possible to include a mere amount of the sub-criteria identified as important. As such, in the environmental criterion we included the: non-energy and energy resource consumption, which were grouped together into 'net resource consumption', the '*GHG emissions'* and the *'renewable energy generation'*; in the economic criterion: the capital, operational and maintenance, and utility costs were grouped together into '*net costs*' and '*revenues*'; and in the social criterion: the '*acceptability'* of the food waste management option, '*health & safety'*, '*odour* and '*noise implications'*.

To facilitate data collection a methodological approach was developed, as summarised in Table S1.

Table S1 Methodological approach in calculating the performance of both food waste management options

Criteria	Sub-criteria	FWDs	Anaerobic co-digestion
ENVIRONMENTAL	*Net resource consumption*	Calculated based on: • Water consumption for grinding (household) • Energy consumption for food waste grinding (household) • Energy consumption for water treatment and distribution, wastewater pumping and treatment and sludge management and disposal (water industry)	Calculated based on: • Fossil fuel consumption for food waste collection and transport to mechanical treatment facility of WWTPs (LAs) • Land requirements for waste processing facilities (water industry) • Energy consumption for food waste processing (water industry) • Additional energy consumption for heating-up the digester (water industry)
	GHG emissions	Calculated based on: • Replacement of FWDs and disposal emissions of previous model based on lifetime span (household/WEEE management options) • Energy consumption for the grinding of food waste (household) • Energy consumption for the extraction and treatment of water used by the FWDs • Energy consumption for the pumping and treatment of additional wastewater generated (water industry) • Energy consumption for the management of the additional sludge produced (water industry) • Exhaust emissions for trucks responsible for the loading, transport and disposal of additional digestate produced (water industry)	Calculated based on: • Exhaust emissions from food waste collection trucks, and transport to the pre-treatment facilities (LAs) • Energy consumption for the construction and operation of a food waste mechanical pre-treatment facility (water industry) • Energy consumption for heating up the digester due to increased water content of food waste (water industry) • Exhaust emissions for trucks responsible for the loading, transport and disposal of additional digestate produced (water industry)
	Renewable energy generation	Calculated based on the biogas/CH_4 generation from additional sewage sludge produced at the wastewater treatment plants (WWTPs) due the use of FWDs (water industry)	Calculated based on the biogas/CH_4 generation from the digestion of food waste together with sewage sludge (water industry)

ECONOMIC	*Net costs*	Calculated using the cost of: • Purchase and installation of a FWD (household) • Maintenance of the FWD (household) • Energy consumption for using the FWD (household) • Replacement and maintenance of sewer pipes (water industry) • Water treatment and distribution (water industry) • Wastewater treatment (water industry) • Sludge management (water industry) • Digestate disposal (water industry)	Calculated using the cost of: • Collection of food waste separately from other waste streams (LAs) • Transport of food waste to the waste management facilities (LAs) • Gate fee for food waste delivery at WWTPs (LAs) • Investment cost for the pre-treatment facilities adjacent to AD (water industry) • Operational cost of food waste pre-treatment (water industry) • Additional heating of the digester due to the addition of food waste load (water industry) • Biogas cleaning equipment (water industry) • Scaling of CHP engines for biogas utilisation (water industry) • Digestate disposal (water industry)
	Revenue	• Benefit of reduction in cost of collection and transport (LAs) • Benefit from renewable energy generation from the additional sludge digestion (water industry)	• Benefit from the treatment of food waste at the WWTPs (LAs) • Benefit from additional renewable energy generation (water industry)
SOCIAL	*Acceptability*	Conducting survey questionnaire and focus groups involving public's participation for reflecting on: • Acceptance of food waste management at source (household) • Response/ concerns to hygiene related (household) • Response/concerns related to odours emissions (household) • Response/concerns related to noise implications (household)	Conducting survey questionnaire and focus groups involving public's participation for reflecting on: • Acceptance of food waste management at source (household) • Response/ concerns to hygiene related (household) • Response/concerns related to odours emissions (household) • Response/concerns related to noise implications (household)
	Health & safety		
	Odour implications		
	Noise implications		

All calculations were performed based on a tonne of food waste processed and collected for processing. Additionally, it was assumed that FWDs can grind everything (at 100% rate; although this is not feasible) and that no regulatory constraints may limit any stage of the two processes. It must be highlighted that while the data that has been collected from the literature came from different sources this was sufficient for the analysis, which aimed to demonstrate how the sustainability framework developed could be applied in the Anglian region.

For *net resource consumption*, water consumption for grinding a tonne of food waste is 11.7 mega litre (Thomas, 2010). Due to the inherent complexity associated with water extraction, treatment and distribution, as well as associated costs and carbon emissions, additional information on this resource consumption was excluded from the analysis; hence the reason that net resource consumption was expressed in kWh per tonne food waste in both processes. However, in real analyses water consumption associated with the use of FWDs (and any other alternative) in the Anglian water region, which is one of the driest regions in the UK, is an important sub-criterion that must be taken into account. In the use of FWDs, the energy consumption was calculated based on the electricity required for grinding food waste, which was estimated based on the energy consumption per use, the frequency and duration of use of the unit for the grinding of a tonne of food waste generated using the UK domestic electricity price conversion factor of 12.89p per kWh (MTP 2008). Food waste's subsequent treatment in the wastewater treatment plant (WWTP) were calculated based on the cost of electricity (in the WWTPs) and the UK industrial electricity price of 7.89 p per kWh, for which details can be found in the Anglian Water Services June Return 2010-11 (DECC 2011; Monson et al. 2007; Ofwat 2011). Sewer cleansing and maintenance was excluded in the analysis mainly because there are no direct costs associated with the disposal of food waste in the sewer. *GHG emissions* were expressed in carbon emission equivalents (kg CO_2 eq); with missions from the burning of fossil fuels (diesel) and electricity consumption estimated using the latest conversion factors of 2.67 kg CO_2eq per litre diesel and 0.525 kg CO_2eq per kWh, respectively (Carbon Trust 2012). *Renewable energy generation* from the use of FWDs, is reported to be the equivalent of 0.048 tonnes of CH_4 (Diggelman and Ham 2003).

For anaerobic co-digestion of separately collected food waste with sewage sludge, *net resource consumption* was calculated based on the amount of fuel consumption during the collection and transport of food waste, which was expressed in kWh per tonne food waste using a conversion factor of 10.89 kWh per litre diesel burnt, and also from the processing of food waste at the waste management facilities using a figure of 68.6kWh per tonne food waste (Banks et al. 2011; Burnley et al. 2011; Carbon Trust 2012). Water consumption and land requirements were not included in the analysis, due to time constraints in collecting the associated data. However, both sub-criteria constitute important aspects of the overall assessment and must be included in the analyses for supporting decision-making. *GHG emissions* were expressed in carbon emission equivalents (kg CO_2 eq); with missions from the burning of fossil fuels (diesel) and electricity consumption estimated using the latest conversion factors of 2.67 kg CO_2eq per litre diesel and 0.525 kg CO_2eq per kWh, respectively (Carbon Trust 2012). A tonne of food waste digested was reported to give 260 m^3 of biogas of which 60% was CH_4 (European Commission 2001). Based on these, and using the CH_4 calorific value of 13.93 kWh per kg, the *renewable energy generated* was calculated (Tchobanoglous and Burton 2003).

The cost of electricity for grinding food waste was estimated based on the UK domestic electricity price conversion factor of 12.89 p per kWh. This cost, together with the cost of sewage collection and treatment and sludge treatment and disposal, based on the latest data provided by the Anglian Water (Ofwat 2011), was used to calculate the costs for the use of FWDs. Because of the difficulty in separating the capital, operational and maintenance and utility costs to the water industry, these were aggregated into *net costs*. Sewer cleansing and maintenance, while constituting an important cost, were not calculated in the analysis mainly because there are no direct costs associated with the disposal of food waste in the sewer. The *net costs* for the anaerobic co-digestion of food waste with sewage sludge was calculated based on the cost of food waste collection, transport and digestion with sewage sludge at the WWTP. The cost of waste collection was based on data from LAs in the Anglian water region adopted from the study of Iacovidou et al. (2012), whereas the cost of transport was calculated based on a figure of 6.5 litres per tonne food waste transport and a gate fee cost of £52 (Burnley 2001; Iacovidou et al. 2012b; WRAP 2009). The Operational Cost of pre-treatment and digestion was based on a figure of £55 per tonne food waste processed, which covered the cost of plant construction, operating and disposal of by-products (Eunomia 2007; Monson et al. 2007). *Revenue* from renewable energy generation was based on the recent renewable energy price of £100 per 1 MWh generated (WRAP 2008); whereas savings from reduction in cost of collection when using FWDs was not included in this analysis.

Social sub-criteria were evaluated based on a qualitative analysis. For this analysis, data related to householders' response and acceptance of the implementation of each food waste management option, and in health and safety considerations, and odour and noise concerns, were collated from the literature. Because of the inherent difficulty in differentiating householders' response into a wider scale of measurement, it was considered appropriate to use a scale of two degrees of measurement (+/++), with + being used for the process with the least positive response, and ++ for the process with the higher positive response. In terms of a*cceptability*, the use of FWDs was reported to be associated with some unwillingness, as a number of householders found their use annoying due to noise implications and laziness (Evans 2007). With regards to the anaerobic co-digestion of food waste with sewage sludge, the separation of food waste at source and its collection was reported to cause unwillingness of some people to participate, mainly because of concerns associated with hygiene, odours and vermin attraction issues (WRAP 2009). However, the majority of people involved in separate collection responded positively to it. Based on that it was assumed that anaerobic co-digestion of food waste is likely to be a more acceptable process that the use of FWDs. The storage and rotting of food and its subsequent collection and handling, can have an impact on the *health and safety* of the personnel involved in the collection and treatment of food waste (CECED 2003). Inhalation of the odorous emissions from food degradation, such as volatile organic compounds (VOCs), sulphur compounds, amines and aromatic hydrocarbons, can cause nausea, bronchitis and gastrointestinal problems to a high level exposure (Defra 2007). *Health and safety* impacts related to the disposal of food waste into the sink have not been as widely reported. Therefore, it was assumed that the use of FWDs has a more positive effect to human health than anaerobic co-digestion with sewage sludge. The storage of food waste in households can be associated with *odour implications* (CECED 2003). Food waste grinding into the FWDs has been reported not to release any kind of unpleasant odours, though food waste disposed into the sewer has the possibility of producing some. The anaerobic degradation of food waste particles in the sewer leads to the production of sulphide, which then forms hydrogen sulphide, the principal cause of malodours, even at very low concentrations (Iacovidou et al. 2012a). As such, FWDs may be more preferable when it comes to *odour implications* that the anaerobic co-digestion with sewage sludge is. *Noise implications* associated with the use of FWDs can be of a greater magnitude as to when noise comes from the outside of the household. In the study of Evans (2007), it was reported that a number of people chose not to use a FWD, mainly because of the noise implications related to it (Evans 2007). As such, and with limited evidence in the literature with regards to the annoyance caused by the noise generated during the collection of food waste, it was assumed that anaerobic co-digestion with sewage sludge performs better in regards to *noise implications* than the use of FWDs.

Section 2: Criteria and sub-criteria weight assignment

In our study we used the equal weights method. In this method criteria (and their sub-criteria) are assigned equal weights. The sum of the weights of criteria, and that of their sub-criteria must be equal should be equal to 1 (or 100%), to ensure consistency of the weighting assignment. The relative contribution of the sub-criteria to the criteria is presented in Table S2.

The weighting of each sub-criterion corresponds to the number of sub-criteria of each criterion. For instance, the sub-criteria of the environmental, economic and social criterion are three, two and four and as such, they have a weighting of ⅓, ½ and ¼, respectively.

Table S2 Sub-criterion weighting for the food waste management options

Criteria	Weighting	Sub-criteria	Weighting	Individual weighting (%)
Environmental	⅓	Net resource consumption	⅓	11.11
		GHG emissions	⅓	11.11
		Renewable energy generation	⅓	11.11
Economic	⅓	Net costs	½	16.67
		Revenues	½	16.67
Social	⅓	Acceptability	¼	8.33
		Health and safety	¼	8.33
		Odour implications	¼	8.33
		Noise implications	¼	8.33
				100

The individual weighting for each sub-criterion is calculated by multiplying the weight of the criterion by the weight of each individual sub-criterion within each group (Table S2). The sum of the individual weighting of all sub-criteria must then be equal to 100%, to ensure the consistency of the weighting assignment.

Section 3: Sensitivity analysis

A sensitivity analysis was carried out to help us better understand the implications of the equal weighting method in the sustainability assessment of food waste management options. This analysis was performed by increasing or decreasing the weights of the individual criteria/ sub-criteria as a way to reflect the response of the alternatives. If the ranking is found to be highly sensitive to small changes in the criteria weights, a careful review of the weights is recommended. The sub-criteria of net resource consumption (RC), net costs (OC), and smell (odour) implications (SI) and health impacts (HI) were the most sensitive to changes in the weights, and could reverse the ranking of the alternatives (Figure S1).

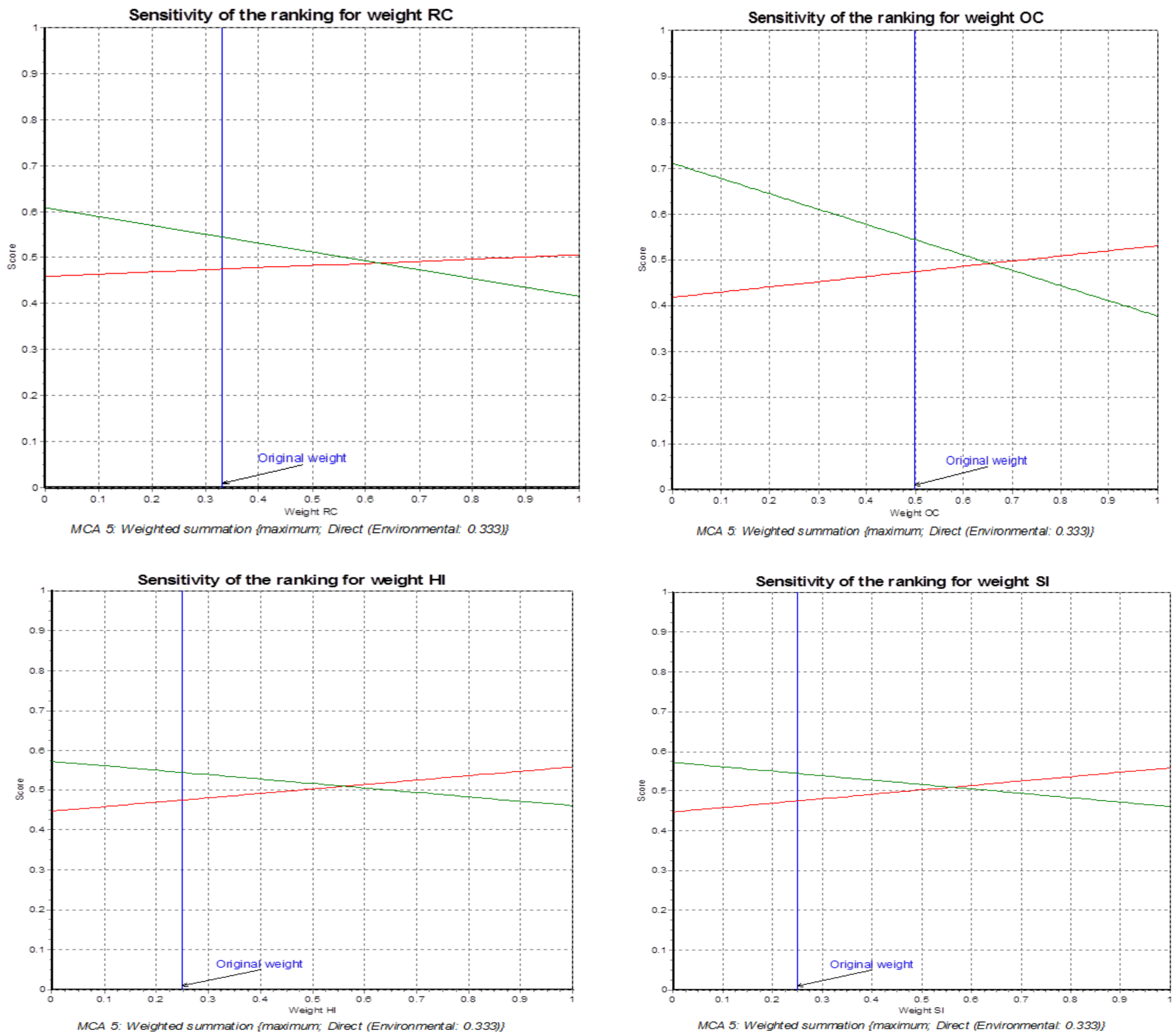

Figure S1 Results of sensitivity analysis of sub-criteria with variation in their weightings; The green line represents anaerobic co-digestion of food waste with sewage sludge, and the red line represents the use of FWDs

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