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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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Abstract

Preventing food wastage is a key element of sustainable resource management. But as food waste is still generated at high volumes, priority should be 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 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 that 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 to adopt. A simplified version of the developed framework was applied in assessing and comparing the two food waste management options in the Anglian region in the UK, indicating that there are benefits in using the framework as a screening tool for identifying which option may be more sustainable, prior to a detailed analysis that incorporates stakeholders' perspectives. An additional use of the framework can be in providing recommendations for optimising food waste management options in a specific region, maximising sustainability performance.

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

1. Introduction

In the UK, it is estimated that 10 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 manufacture, distribution, retail, wholesale and hospitality and food service sectors) are produced each year in the UK, 60% of

which could have been avoided (Facchini et al. 2017). Although, actions have led to a reduction of 1.6 million tonnes in the UK's annual food waste arisings compared to 2007, there is still much to do (WRAP 2016). Legislations such as the EU Landfill Directive (1999/31/EC) and the revised EU Waste Framework Directive (2008/98/EC), mandate EU member states, and currently the UK, to divert biodegradable waste from landfill and promote waste prevention, reuse and recycling, respectively (European Parliament and Council 2008; European Union 1999). However, progress has been slow with modelling suggesting that without any further interventions, food waste may increase by 1.1 million tonnes by 2025 (WRAP 2016).

Although a number of alternatives such as, incineration (Inaba et al. 2010; Khoo et al. 2010), composting (Cerdeira 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; incineration and composting are considered to be the least desirable 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 its successful and efficient performance (Iacovidou et al. 2012b). Anaerobic digestion, despite its prominent place in policy making as a sustainable energy alternative, is considered to be a challenging option, too largely because of the variability of food waste. Two other less widespread alternatives yet critical to the management of food waste, are the use of food waste disposal units (FWDs) and subsequent treatment at wastewater treatment plants (WWTPs), 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 which then goes to the local WWTP. 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.

However, the current debate on the impacts of the use of FWDs on water consumption, sewerage system, and the WWTPs, the value exploitation potential of food waste and the effectiveness of the food waste collection schemes, as well as the 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 owing to the fact that the sustainability potential of these two food waste management options depends largely on the area-specific characteristics, household practices, condition of the sewerage system, and the type of treatment at the receiving WWTP. Therefore the need to evaluate associated environmental, economic and social impacts on a case by case basis, demonstrates that a sustainability tool for assessing and comparing the two options for selecting the most sustainable one, 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 using an explicit set of criteria (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; Garfi et al. 2009).

Therefore this study, by integrating the principles of MCA with sustainability assessment considerations (Ashley et al. 2008; Gudmundsson et al. 2016), presents a framework for comparing the sustainability performance of food waste management options in the UK based on area-specific characteristics, supporting decision-making (Section 2). Using the Anglian water region as a case study, the framework developed is used to compare the sustainability performance of the two increasingly popular food waste management options in the UK - the use of FWDs and the anaerobic co-digestion of food waste with sewage sludge -, and provide some findings on the applicability of the framework and its potential to aid the comparison between the use of FWDs and the anaerobic co-digestion of food waste with sewage sludge (Section 3). Then, we discuss some of the key outcomes of the study (Section 4), and provide some concluding remarks in Section 5.

2. The sustainability assessment framework

The key objective of our sustainability assessment framework (SAF) is to compare the sustainability performance of food waste management options (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, as this is one of the foremost critical aspects of a robust food waste management assessment process. Then the food waste management alternatives that are to be evaluated and compared are identified pertained to the specific context set by the stakeholders (Fig. 1). Measuring sustainability of the identified 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.

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. As such, in this study the identification of sub-criteria is guided by three clearly outlined phases, namely 1) the mass balance configuration; 2) the governance and institutional context (e.g. policies, and other socio-economic drivers) assessment; and 3) the stakeholders' values; shown in Fig. 1. 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 it 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 in our study and using the framework as a screening tool, yet phase 3 reinforces sub-criteria selection and stipulates aspects that could be otherwise overlooked and should be included in the analysis when possible.

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

Following the selection of the sub-criteria, the quantitative and qualitative data collection and assessment for calculating their performance, is performed. An evaluation matrix that contains the estimates (scores) of each sub-criterion 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 organization 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 the essence of the 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.) | [1-4,14,15] |
| | Energy resource consumption | [2-11,14,15] |
| | Global warming potential (or else known as greenhouse gas emissions, GHG) | [1-6,8-12,15] |

| | | |
|-----------------|--|-------------------------|
| | Human toxicity potential (HTP) | [1, 4, 5, 10, 12,14,15] |
| | Photochemical ozone formation potential (POFP) | [1, 3, 5, 6, 10, 11,15] |
| | Acidification potential | [1-6, 9-12, 15] |
| | Eutrophication potential | [1-6, 10-12, 15] |
| | Ozone depletion potential | [2, 3, 5, 9, 10, 15] |
| | Ecotoxicity potential | [4, 5, 12, 15] |
| | Land use (incl. transformation) | [1, 15] |
| | 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, 15] |
| 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] |

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); [15] {Manfredi, 2012 #79}

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, and the reliability, efficiency and resilience of technologies over time, as well as 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). Section 3 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

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 is one of the areas with the fastest growing population in the UK. According to the Environment Agency 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). Besides the above considerations, constraints in holding the participatory approach as a prerequisite of Phase 3: stakeholders' perceptions, interests and drivers, the Anglian water region 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; Iacovidou et al. 2012b; Iacovidou et al. 2012c).

Identification of alternatives: the use of FWDs, and the anaerobic co-digestion of separately collected food waste with sewage sludge are the two alternatives considered in this study as these were defined in the Introduction section.

Selection of sub-criteria: for the selection of sub-criteria for the sustainability assessment of the two alternatives, 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. The UK government's commitment to divert food waste from landfill and to increase renewable energy generation 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). In assessing the sustainability of their performance in the Anglian region (as well as in any region in the UK), a web of systemic factors associated with the population and/or households served (and the number of occupants per household) by each option within 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 for a correct distribution of impacts. 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 for assessing the sustainability of the use of FWDs. For the 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.

We considered the degree at which environmental permitting regulations, landfill tax and financial incentives can affect the prevalence of the one option over the other. 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 pasteurized or sterilized 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 produce 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 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 from the other waste streams 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), FWDs 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 comparative; yet information on those aspects is still lacking.

Based on the above analysis, 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 a FWD, 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 (downstream) (Møller et al. 2009). The latter may vary based on the type of digester used, and the distribution/utilization 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 regards 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 (NO_x) 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 Micalè 2015). Risks to human health from the storage and decomposition of food waste in the household may occur via the inhaling 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) and 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 capacity of an 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 regards 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 fuels

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:** includes 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 mere amount 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 & 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 et al. (2001).

The sub-criteria used in the analysis are measured in a variety of 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 standardize 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 weighting, 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 a score 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, and (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 $\pm 50\%$ from initial ones, 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 understand 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.

4. Discussion

While the SAF developed was employed for comparing 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, it may have not allowed for a comprehensive analysis of the two options 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. The form of this value may vary from one treatment process to another; for example we have biogas and digestate produced from the anaerobic co-digestion of food waste with sewage sludge, but an improved wastewater treatment process due to increased organic load and environmental and cost savings from the absence of food waste collection 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, and the governance and institutional contexts 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-fetched (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 to be reflected on the decision-making process. A participatory approach that requires all stakeholders, that 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 performing the sustainability assessment framework. 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 used in sustainability assessment processes, 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.

5. Conclusions

Food waste is a valuable resource than can be turned into an opportunity, if the area-specific characteristics and practices implemented for its treatment are taken into account. This the basic principle of sustainability assessment framework (SAF) developed in this study, which can be effectively used as a screening and 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 to support decision-making. 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 work 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.

6. References

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