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Optimising industrial food waste management

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Abstract

Global levels of food waste are attracting growing concern and require immediate action to mitigate their negative ecological and socio-economic ramifications. In the developed world, of the order of 20-40% of food waste is generated at the manufacturing stage of supply chains and is often managed in non-optimised ways leading to additional environmental impacts. This research describes a novel decision-support tool to enable food manufacturers to evaluate a range of waste management options and identify the most sustainable solution. A nine-stage qualitative evaluation tool is used in conjunction with a number of quantitative parameters to assess industrial food waste, which is then used to generate performance factors that enable the evaluation of economic, environmental and social implications of a range of food-waste management alternatives. The applicability of this process in a software-based decision-support tool is discussed in the context of two industrial case studies.

Keywords: food waste; waste management; sustainability; food manufacturing

1. Introduction

Achieving global food security is a challenge that necessitates a set of actions to be established and accomplished by numerous actors, including supranational organisations, governments, non-governmental organisations, food companies, retailers and consumers. One approach to increase food availability for societies with low economic incomes is to reduce food-waste volumes and redirect surplus food to people in need. It is estimated that just 25% of the global food waste would be enough to feed all the hungry people worldwide [1].

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In the UK, most food waste is generated at only two stages of the supply chain: during manufacture and at the consumption stage. Currently, several initiatives seek into raise consumer awareness of the costs of food waste and provide advice on how to prevent food from becoming waste (e.g. Love Food Hate Waste [2]). However, there are fewer such joint attempts to reduce manufacturers' food waste and therefore food companies usually must identify and implement their own waste management and prevention solutions. Consequently, the food industry often manages its food waste in non-optimised ways, basing decisions on a limited number of factors such as costs, availability of waste management facilities and resource requirement to implement the solution. Additionally, large proportions of industrial food waste are unavoidable [3], which are commonly known as food by-products, implying food-waste management is necessary rather than preventive measures in some cases. Food-waste management alternatives (FWMAs) in the UK food industry have been quantified [4,5], as can be seen in Fig. 1, concluding that most of the industrial food waste in the UK cannot be reduced (i.e. it is unavoidable) and a range of different FWMAs are required, covering all the levels of the food-waste management hierarchy. Currently, around half of the food waste (including inedible materials) in the UK supply chain is produced at the manufacturing stage [4].

There is limited (and less reliable) information available for food waste generated at the manufacturing sector in the rest of European countries [6]. An approximate proportion of industrial food waste and by-products in supply chains of some large developed areas of the world is estimated in Table 1. It can be concluded that, in spite of the high variability, manufacturers contribute significantly to food waste quantities in the developed world. It must be also noted that different definitions and methodologies to quantify food waste are used in different regions. A harmonised methodology to quantify food waste in the supply chain, which should be followed to compare results of different countries, has been recently published by FUSIONS [7]. The high variability on food-waste proportions in the industrial stage of developed nations' supply chains can be explained by the size of the food-industry sector in the region, type of food produced (e.g. perishable foods or preserved foods), different regulations and government encouragement to reduce food waste, etc.

As a result, an increasing number of articles have been published to address this problem and propose software solutions or decision-support tools. Chang *et al.* [8] published an extensive review of simulation and optimisation models for solid waste management developed before 2010, highlighting the lack of a whole waste-management cycle approach. Relevant decision-support tools focused on sustainability issues of waste management have been proposed by various authors [9-11]. Karmperis *et al.* discusses different decision-support models with a focus on the applicability of game-theoretic approaches [12]. Soltani *et al.* also explores game-theoretic methods and introduces a weighing system to assess impacts of waste-to-energy technologies [13]. Additional research in this area has been
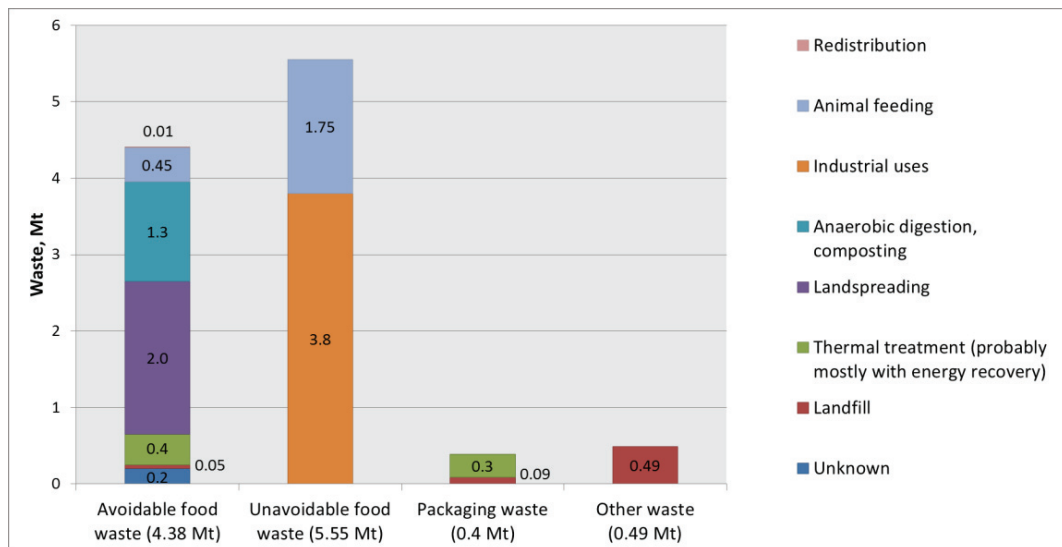

Fig. 1. Quantification of food-waste management alternatives (FWMAs) in the UK food industry. Data from WRAP [4,5]

carried out by Wang *et al.* applying a fuzzy-stochastic programming approach [14] and Rojo *et al.* [15] using a dynamic waste management approach. On the other hand, Hannan *et al.* reviewed recent developments of existing information and communication technologies (ICT) and their usage in solid waste management, which could facilitate data collection necessary for the decision-making with regard to waste management [16]. The authors believe this recently highly-populated area of research will benefit from a holistic approach that will serve to identify the most relevant attributes and their interrelationships to model food-waste management systems.

Table 1. Proportion of industrial (edible and inedible) food waste in food supply chains of some large developed areas of the world. [a]The European Commission does not include agricultural food waste into its calculations. [b]Includes industrial food by-products (i.e. unavoidable waste) which WRAP does not consider as food waste. [c]Does not include animal feeding or materials sent for biochemicals processing.

	Food waste in the supply chain, Mt	Industrial food waste, Mt	Percentage of total food waste generated at the manufacturing stage	References
US	67 – 134	20	15 – 30%	[17,18]
Japan	18	3 – 4	17 – 22%	[19]
Germany[a]	12.3	1.85	15%	[20]
France[a]	8.59	0.63	7%	[20]
Italy[a]	5.66	10.5	54%	[20]
UK[b]	19.25	9.93	52%	[4]
EU-27[a]	89.2	34.8	39%	[20]
EU-28[c]	87.6	16.9	19%	[21]

This paper outlines a novel decision-making procedure that can be used to address food-waste management issues from a broader perspective, considering direct and indirect ramifications of different possible solutions. It can be used as a framework with the following structure: a definition of parameters, data collection to value the aforementioned parameters, processing of information using mathematical models and the generation of a recommendation to increase sustainability of food-waste management. The procedure has been designed with the aim to be universally applicable, for all types of food waste, and considering five different waste-management alternatives. The links between different attributes are discussed and the practicality of this process in a software-based decision-support tool is explained in this paper. Two industrial case studies are used as samples to test the applicability of the proposed decision-making process.

2. Research methodology

In order to improve waste-management practices in the food industry a sound understanding of various elements involved in the process is needed:

1. Food waste: to comprehend characteristics of raw material to be managed (i.e. food waste).
2. Food-waste management alternatives (FWMAs): to be aware of the available waste management options and understand their performance.
3. Sustainability ramifications: to recognise ecologic and socio-economic consequences of different waste management practices.

This scheme, as described in Fig. 2, incorporates the determination of qualitative and quantitative parameters to estimate characteristics of food wastes, variables to model waste management processes and company status, factors to evaluate the performance of waste management practices, and key sustainability indicators to assess ramifications of FWMAs. The assessment of these indicators will help to select a tailored waste management practice that optimises the outputs generated.
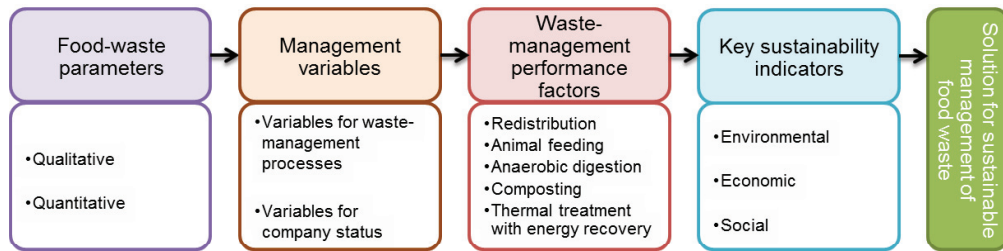
Fig. 2. Decision-making process and attributes to select sustainable solutions for food-waste management.

The first stage of the decision-making process is the selection of the relevant attributes to understand the aforementioned elements, which needs adjustments for each particular case. For instance, in order to treat milk waste the pH value is necessary, as opposed to meat waste, where the carbon-nitrogen relation (C:N) is more relevant. Secondly, the attributes identified must be linked to each other in a way that interrelationships are built. This necessitates a mathematical-modelling process that enables the estimation of an attribute's value through previously-obtained values of other attributes, e.g. the composition of toxic gases emitted to the atmosphere can be estimated knowing the characteristics of both food waste and the incineration process utilised. Thirdly, for the attributes that cannot be estimated through calculations from other attributes data must be collected, e.g. the carbohydrate content of food waste cannot be calculated from other attributes and therefore must be obtained from databases, previously published research or using analytical methods. Finally, the sustainability values generated for each FWMA are compared using a pre-established criterion. Combining these indicators allows a solution for sustainable food-waste management to be proposed. The key attributes identified to complete the first stage of this process are classified and characterised in the following sections.

The attributes needed to model waste management performance are dependent on the different FWMAs. In this work, the following FWMAs are considered: redistribution for human consumption, animal feeding, anaerobic digestion, composting and thermal treatments with energy recovery. The following FWMAs fall out of the scope of this paper: industrial uses, as its assessment will be needed for each individual food-waste type; and landspreading, thermal treatments without energy recovery and landfilling, because other possibilities are always prioritised due to their larger benefits.

3. Stages of the decision-making procedure

This section defines the data needed to characterise FWMAs. Each of the stages of the process is described, and the most relevant parameter, variable, factor and indicator of each type is identified and classified in Table 2.

Table 2. Examples of parameters, variables, factors and indicators to model food-waste management alternatives. FWMA, food-waste management alternative; R, redistribution for human consumption; AF, animal feeding; AD, anaerobic digestion; C, composting; and TT, thermal treatment with energy recovery.

	FWMA	Example of parameter, variable, factor or indicator	Example of value or unit	References
Qualitative parameters	R	Edibility	Edible / Inedible	[22]
Quantitative / Primary parameters	R, AF, AD, C, TT	Flow rate	(kg or m^3)/day	
Quantitative / Secondary parameters	AD, C, TT	Volatile solids (VS)	% of total solids (TS)	[23-25]
Process variables	AD, C, TT	Temperature	°C	[23-25]
Company variables	C	Pile size available	cm high, m wide	[26]
Performance factors	AD	Methane yield	L/(g VS)	[23]
Environmental indicators	R, AF, AD, C, TT	Greenhouse gas emissions	(kg CO_2 eq)/day	[27]
Economic indicators	R, AF, AD, C, TT	Economic income	£/month	
Social indicators	R	Feasibility to redistribute	Yes / No	

3.1. Parameters to estimate characteristics of food wastes

Food wastes are very diverse in their characteristics and composition. In this paper, all types of food waste that generates an economic cost or smaller benefit than predicted to the food business are considered, for instance unavoidable food waste and surplus food that could not be sold and so sent for redistribution to people in need or animal feeding. Packaging waste is only considered when it contains a food product (i.e. packaged food), but not separately.

Parameters to estimate characteristics of food wastes are classified into two categories (qualitative and quantitative parameters) and two sub-categories (for quantitative parameters, primary and secondary parameters), which are defined below and exemplified in Table 2.

Qualitative parameters have Boolean values and do not refer to a numerical value. A set of nine parameters, from Garcia *et al.* [23], are used in this research: edibility, state, origin, complexity, animal-product presence, treatment, packaging, packaging biodegradability and stage of the supply chain. An assessment of these characteristics provides initial guidance to select the most appropriate FWMA.

Quantitative parameters provide more specific and quantitative information about the characteristics of the food waste and are further classified in primary and secondary parameters as explained below:

- **Primary parameters** cannot be determined by other parameters. In order to obtain the value for primary parameters, experimental analysis, review of published literature or data collection from databases must be carried out. The values of primary parameters are intrinsic to the type and quantity of food waste under consideration, e.g. chemical composition.
- **Secondary parameters** can be calculated using values of primary parameters. In order to do so, mathematical relations must be built between secondary and primary parameters. Additionally, secondary parameters can be also obtained from experimental analysis, published literature or databases. Secondary parameters must be defined when considering different FWMAs, e.g. volatile fatty acids (which depend on fat content and composition) when assessing anaerobic digestion of food waste.

Some of the parameters described in this section are also relevant to evaluate the performance of the processes, e.g. the final pH and the lowest pH gives information about the yield of the composting process [28]; additionally the value of some parameters can be corrected during the treatment (e.g. addition of a buffer to control pH in the anaerobic digester) and therefore can be also considered waste-management processes variables. These types of parameters should be monitored during the process and evaluated at the end of the treatment as performance factors.

3.2. Variables to model waste management processes and company status

In addition to parameters based on food-waste characteristics, there are a number of variables which depends on other factors (i.e. external variables). They can be classified in two large categories: waste-management processes and company status variables. These categories are defined below and exemplified in the Table 2.

Waste-management processes variables need to be defined in order to evaluate the performance of the different alternatives, e.g. the temperature in the bioreactor is a key variable in order to obtain the maximum amount of biogas in an anaerobic digester. Clearly, the variables must be different for each FWMA considered. The values of these variables must be determined for each batch and type of food waste treated, since optimum values are unlike for different feedstocks (e.g. solid and liquid food waste) and situations (e.g. different levels of ripeness for the same type of food will cause variations in chemical compositions of the waste). As justified in Section 2, the following FWMAs are studied in this research: redistribution for human consumption, animal feeding, anaerobic digestion, composting and thermal treatments with energy recovery.

Some of the waste-management process variables are also relevant to evaluate the performance of the processes, e.g. the concentration of oxygen in the composted material [26]. This type of parameters should be monitored during the process and evaluated at the end of the treatment as performance factors.

Company status variables will not change from batch to batch as they are constant for a certain food company (i.e. fixed variables). For instance, the type of equipment to treat food waste available in the factory, or the distance

to waste processors that take charge of the waste will generally remain unchanged. Clearly, these variables may also change over longer periods, e.g. new equipment can be purchased, but these variables will be considered fixed variables as the time to implement the changes is longer than the time given to manage food waste. When the variables (or their values) change, they will have to be amended in the model.

3.3. Factors to evaluate the performance of waste management practices

Once the aforementioned data has been collected and introduced in the tool, the performance of the different FWMAs can be estimated through a bespoke modelling of the different processes. For this purpose, firstly a set of factors to evaluate the performance of waste management practices must be defined for each FWMA considered. For instance, for anaerobic digestion the amount of biogas and its methane content will be the most relevant factors (as illustrated in Table 2). Secondly, these factors will have to be linked to the parameters and variables described in Sections 3.1 and 3.2, in a way that mathematical connections are formulated. As a result, the value of these factors can be calculated using previously assessed parameters and variables.

3.4. Key sustainability indicators to assess ramifications of FWMAs

In order to compare the results obtained from different FWMAs, their performance factors must be first converted into comparable indicators. Since the aim of this research is to increase the sustainability of food-waste management, the indicators chosen are associated to the three pillars of sustainability: environmental, economic and social ramifications, as described below and exemplified in Table 2.

Environmental indicators evaluate the impact on the environment (e.g. air, water, soil) of the different FWMAs. These impacts are generally negative (e.g. toxic gases emitted), but can also be positive in certain occasions (e.g. use of waste for the removal of pollutants in wastewater).

Economic indicators are used to assess the economic result from food-waste management, which can be either positive (economic benefit obtained from management of the waste) or negative (economic cost to dispose of the waste). FWMAs with worse economic output than currently-followed alternatives can be discarded at this stage.

Social indicators incorporate social considerations not addressed with environmental and economic indicators. They can also be either positive (e.g. decrease in food prices) or negative (e.g. increased taxes). Because of the complexity and vast variety of potential social ramifications from food-waste management, the social analysis undertaken in this research is focused only on feasibility to redistribute food fit for human consumption.

Again, mathematical models are needed to link the key sustainability indicators defined with the various factors to evaluate the performance of waste management practices. It must be noted that the sustainability indicators refer to the ramifications generated since the moment the food waste is produced until the management of the waste is finished (including transportation). Impacts related to the production of the food, its harvesting, storage, manufacturing, etc., have not been considered, as they will not influence the decision-making to manage food waste because they have already happened before food waste was generated. Therefore, a life-cycle approach was not appropriate for this paper.

4. Applicability of the model in a software-based decision-support tool and case studies

The parameters, variables, factors and indicators described in the previous sections can be used to model different solutions for food-waste management. Incorporating these considerations into a software tool enables manufacturers to gain information on different FWMA performances and their ramifications, and as a result a selection of the most sustainable solution to manage each type of food waste can be made. This decision will be assisted by a decision-support tool system which will be part of the software program. Consequently, the software tool is envisaged to be used mainly by waste managers in food manufacturing companies or members of staff with similar roles and duties in the food sector. Due to the different backgrounds and the huge dissimilarities amongst different food manufacturers, the interface is intended to be simple and user-friendly.

The software will be based in Microsoft Excel spreadsheets and MATLAB. Once the computer program is started, the user will see windows where the data needs to be introduced. This will be done selecting a parameter

from a list of options in a dropdown menu (e.g. "edible" for qualitative parameters) or typing a numerical value in a box (e.g. C:N ratio "25" for quantitative parameters). The user will have to add all relevant data for both qualitative and quantitative food-waste parameters, and for both waste-management processes variables and company status variables. In a future development of this research the software will incorporate a database with the most relevant food-waste parameters, therefore the user will just have to select the food waste to manage from a dropdown menu and its associated parameters will be added automatically to the system.

The software will work following the process shown in Fig. 2. Once the data is added to the program, the software processes the information for each FWMA and calculates the values for each waste-management performance factors identified, using a set of mathematical models built in the system. These mathematical models are collected from a review of state-of-art literature in the relevant technologies (i.e. FWMAs) considered. In the same way, additional mathematical models incorporated in the software will convert waste-management performance factors into sustainability indicators, thus the indicators used when assessing FWMAs will be alike and therefore comparable (e.g. greenhouse gas emissions). As a result, the decision can be made to maximise positive outcomes and minimise negative ramifications. The decision-support tool will be designed in a way that the indicators will be weighed according to their relevance in food-waste management decisions, e.g. prioritising particle emissions to odour, or prioritising economic ramifications to environmental impacts. This prioritisation criterion is subjective and variable; therefore the weighing of indicators will be open to be amended by the user according to their needs and judgement.

The approach and terminology explained in this work has been applied to study different types of food waste generated at the industrial sites of two leading UK food manufacturers: Molson Coors, a brewing company; and Quorn Foods, a manufacturer of meat alternatives. Several types of food waste were identified in both companies and one for each business was selected to illustrate the applicability of this work (Fig. 3). In Molson Coors, the most significant food waste is the spent grain removed after the mashing process, which accounts for about 85% of the total food waste generated at the plant. In Quorn Foods, food-product returns was selected due to its high use of resources, as this is the final product that has undergone all the production process but cannot be sold due to a number of reasons, such as packaging errors, incorrect formulation, etc. The most relevant parameters, variables, factors and indicators were identified for each type of food waste. This approach is useful to compare the performance of the alternatives followed to manage food waste and also to identify and analyse potential improvements and alternative options to manage food waste.

5. Conclusions

This research presents a decision-making procedure to optimise industrial food-waste management. A terminology and decision-making process has been defined, which includes the description and identification of the most relevant parameters, variables, factors and indicators to model FWMAs. The applicability of the model described in a software-based decision-support tool has been discussed, and the practicality of the approach has been

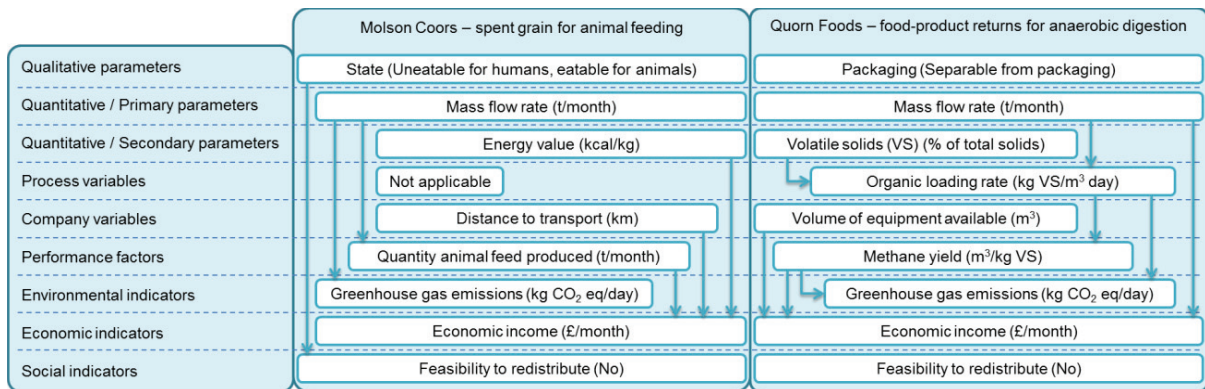|	Molson Coors – spent grain for animal feeding	Quorn Foods – food-product returns for anaerobic digestion
Qualitative parameters	State (Uneatable for humans, eatable for animals)	Packaging (Separable from packaging)
Quantitative / Primary parameters	Mass flow rate (t/month)	Mass flow rate (t/month)
Quantitative / Secondary parameters	Energy value (kcal/kg)	Volatile solids (VS) (% of total solids)
Process variables	Not applicable	Organic loading rate (kg VS/m³ day)
Company variables	Distance to transport (km)	Volume of equipment available (m³)
Performance factors	Quantity animal feed produced (t/month)	Methane yield (m³/kg VS)
Environmental indicators	Greenhouse gas emissions (kg CO_2 eq/day)	Greenhouse gas emissions (kg CO_2 eq/day)
Economic indicators	Economic income (£/month)	Economic income (£/month)
Social indicators	Feasibility to redistribute (No)	Feasibility to redistribute (No)

Fig. 3. Most relevant parameters, variables, factors and indicators to model food-waste management alternatives at Molson Coors and Quorn Foods manufacturing plants. The most relevant interrelationships between attributes are shown with arrows.

tested through two industrial case studies. Further work includes the identification of additional attributes which can be relevant to different FWMAs and the incorporation of their mathematical interrelationships into a software tool. As a result, the software tool will assess the environmental, economic and social performance of different solutions and inform the user of the best alternative to increase sustainability in food-waste management.

Acknowledgements

References

[1] FAO [Online]. www.fao.org/save-food/resources/keyfindings/en/. [Accessed: 4/4/2016].
[2] WRAP [Online]. www.lovefoodhatewaste.com. [Accessed: 5/4/2016].
[3] M. Bond, T. Meacham, R. Bhunnoo, T. Benton. Food waste within global food systems (2013). Global Food Security.
[4] WRAP. Estimates of food and packaging waste in the UK grocery retail and hospitality supply chain (2015).
[5] P. Whitehead, J. Parfitt, K. Bojczuk, and K. James. Estimates of waste in the food and drink supply chain (2013). WRAP.
[6] K.-R. Bräutigam, J. Jörissen, C. Priefer. The extent of food waste generation across EU-27: Different calculation methods and the reliability of their results, Waste Manag. Res., vol. 32 no. 8 (2014) pp. 683–694.
[7] FUSIONS. Food waste quantification manual to monitor food waste amounts and progression (2016).
[8] N.-B. Chang, A. Pires, G. Martinho. Empowering Systems Analysis for Solid Waste Management: Challenges, Trends, and Perspectives, Crit. Rev. Environ. Sci. Technol., vol. 41 no. 16 (2011) pp. 1449–1530.
[9] K. W. Harrison, R. D. Dumas, E. Solano, M. A. Barlaz, E. J. Downey Brill, S. R. Ranjithan. Decision support tool for life-cycle-based solid waste management, J. Comput. Civ. Eng., vol. 15, no. 1, (2001) pp. 44–58.
[10] P. Costi, R. Minciardi, M. Robba, M. Rovatti, R. Sacile. An environmentally sustainable decision model for urban solid waste management, Waste Manag., vol. 24 no. 3 (2004) pp. 277–295.
[11] J. den Boer, E. den Boer, J. Jager. LCA-IWM: A decision support tool for sustainability assessment of waste management systems, Waste Manag., vol. 27 no. 8 (2007) pp. 1032–1045.
[12] A. Karmperis, K. Aravossis, I. Tatsiopoulos, A. Sotirchos. Decision support models for solid waste management: Review and game-theoretic approaches, Waste Manag., vol. 33 no. 5 (2013) pp. 1290-1301.
[13] A. Soltani, R. Sadiq, K. Hewage. Selecting sustainable waste-to-energy technologies for municipal solid waste treatment: A game theory approach for group decision-making, J. Clean. Prod., vol. 113 (2016) pp. 388-399.
[14] S. Wang, G.H. Huanga, B.T. Yang. An interval-valued fuzzy-stochastic programming approach and its application to municipal solid waste management, Environ. Model. Softw., vol. 29 (2012) pp. 24-36.
[15] G. Rojo, M. Glaus, R. Hausler, V. Laforest, J. Bourgeois. Dynamic waste management (DWM): Towards an evolutionary decision-making approach, Waste Manag. Res., vol. 31 no. 12 (2013) pp. 1285-1292.
[16] M.A. Hannan, M. Abdulla Al Mamun, A. Hussain, H. Basri, R.A. Begum. A review on technologies and their usage in solid waste monitoring and management systems: Issues and challenges, Waste Manag., vol. 43 (2015) pp. 509-523.
[17] J. Bloom, American Wasteland. How America Throws Away Nearly Half of Its Food (and What We Can Do About It). Da Capo Press (2011).
[18] BSR. Analysis of U.S. Food Waste Among Food Manufacturers, Retailers, and Wholesalers, April (2013).
[19] F. Marra. Fighting Food Loss and Food Waste in Japan (2013). Leiden University.
[20] European Commission (DG ENV). Preparatory Study on Food Waste Across EU 27 (2010).
[21] FUSIONS. Estimates of European food waste levels (2016).
[22] G. Garcia-Garcia, E. Woolley, S. Rahimifard. A Framework for a More Efficient Approach to Food Waste Management, Int. J. Food Eng., vol. 1 no. 1 (2015) pp. 65–72.
[23] R. Zhang, H. M. El-Mashad, K. Hartman, F. Wang, G. Liu, C. Choate, P. Gamble. Characterization of food waste as feedstock for anaerobic digestion, Bioresour. Technol., vol. 98 no. 4 (2007) pp. 929–935.
[24] J. I. Chang, J. J. Tsai, K. H. Wu. Thermophilic composting of food waste, Bioresour. Technol., vol. 97 no. 1 (2006) pp. 116–122.
[25] I. I. Ahmed, A. K. Gupta. Pyrolysis and gasification of food waste: Syngas characteristics and char gasification kinetics, Appl. Energy, vol. 87 no. 1 (2010) pp. 101–108.
[26] L. Cooperband. The Art and Science of Composting. A resource for farmers and compost producers (2002).
[27] E. den Boer, F. Brouwer, A. Schroten, H. van Essen. Are trucks taking their toll? The environmental, safety and congestion impacts of lorries in the EU (2009).
[28] J. I. Chang, Y. J. Chen, Effects of bulking agents on food waste composting, Bioresour. Technol., vol. 101 no. 15 (2010) pp. 5917–5924.