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Research article

Development of a pragmatic framework to help food and drink manufacturers select the most sustainable food waste valorisation strategy

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ABSTRACT

Food waste is a significant contemporary issue in the UK, with substantial environmental, social and economic costs to the nation. Whilst efforts to reduce food waste are laudable, a significant proportion of food and drink manufacturer waste is unavoidable. On the one hand, there is a drive from industry to reclaim as much value from this waste as possible, for example, by conversion to valuable products in what is known as "valorisation". At the same time, growing social and legislative pressures mean that any attempts to valorise food waste must be performed in a sustainable manner. However, for every company and its specific food wastes, there will be multiple valorisation possibilities and few tools exist that allow food and drink manufacturers to identify which is most profitable and sustainable for them. Such a decision would need to not only consider environmental, social and economic performance, but also how ready the technology is and how well it aligns with that company's strategy. In response, this paper develops and presents a hybrid framework that guides a company in modelling the volumes/seasonality of its wastes, identifying potential valorisation options and selecting appropriate indicators for environmental, social and economic performance as well as technological maturity and alignment with company goals. The framework guides users in analyzing economic and environmental performance using Cost-Benefit Analysis and Life Cycle Assessment respectively. The results can then be ranked alongside those for social performance, technological maturity and alignment with company goals using a weighted sum model variant of Multi-Criteria Decision Analysis to facilitate easy visual comparison. This framework is demonstrated in the form of a case study with a major UK fruit consolidator to identify the optimal strategy for managing their citrus waste. Possibilities identified included sale of imperfect but still edible waste via wholesale at a significantly reduced profit and the investment in facilities to extract higher value pectin from the same waste stream using a microwave assisted pectin extraction process. Results suggest that continued sale of waste to wholesale markets is currently the most beneficial in terms of economic viability and environmental performance, but that in the medium to long term, the projected growth in the market for pectin suggests this could become the most viable strategy.

1. Introduction

In 2015, UK Food and Drink Manufacturing (FDM) accounted for 2.4 million tons (Mt) of food waste and surplus (including both unavoidable and avoidable waste/surplus). Of this, 42 thousand tons (kt) was diverted to secondary markets or charities and 635 kt was sent to animal feeding, whilst the remaining 1.7 Mt was disposed of as waste through methods such as anaerobic digestion, thermal treatment and land spreading (Parfitt et al., 2016a). This represents not just a significant economic loss (4.2% of sales for the sector) but also a significant challenge to Environmental Sustainability with FDM accounting for 8 million tons of CO_2 emissions annually, in addition to substantial emissions to water and land (Riley and Rumsey, 2016). These challenges are not restricted to the UK and a recent United Nations Champions 12.3 report indicates comparable percentages of food waste and associated CO_2 emissions in other developed regions such as North America and the EU (Lipinski et al., 2017). Therefore, whilst this work is based from a UK perspective, it is very much applicable in other developed world nations.

Clearly, continued waste of food at current levels is unacceptable from a business and sustainability perspective and indeed, evidence suggests businesses are taking action. For example, the recent Courtauld Commitment 3 between over 50 UK manufacturers and retailers, aiming to reduce ingredient, product and packaging waste in the

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pre-household stages of the supply chain by 3% between 2012 and 2015, was successfully achieved (WRAP, 2017). However, as successful as such waste reduction goals can be, it must be kept in mind that 1.34 Mt of the FDM waste is not practically avoidable and so new ways of extracting value (referred to as valorisation from here onwards) and ideally, recirculating this waste for human consumption are essential for such Unavoidable Food Waste (UFW) (Parfitt et al., 2016a). Unsurprisingly therefore, the field of food waste valorisation has grown rapidly over recent decades with many publications concerning experimental research into the recovery of energy, nutrients and other high value compounds from food waste (for example, Mirabella et al., 2014 and Kwan et al., 2015). Whilst such technical works are a valuable contribution, for many food and drink manufacturers, particularly small to medium enterprises (SMEs) who make up the majority of the UK FDM sector, there may be challenges in aligning technical valorisation opportunities with a company's bespoke waste situation. This is because a range of factors including economic viability (i.e. costs vs benefits), environmental performance (e.g. emissions, effects on human health), societal impact (e.g. job creation, noise generation), technological maturity (e.g. readiness of technology for valorisation at a lab scale, market readiness for the product and potential of the required technology to integrate with existing company processes) and finally alignment with company goals (strategic alignment, brand image and fit with existing expertise) determine what are likely to be a company's optimal valorisation options (Bernstad and la Cour Jansen, 2011; Iacovidou and Voulvoulis, 2018; Diaz-Balteiro et al., 2017; Cristóbal et al., 2018).

To address the identified research gap, this paper provides a thorough review of the literature in terms of techniques that others have applied to help select ways to valorise food waste. Based on synthesis of the findings, a novel pragmatic framework is presented which facilitates comparison of multiple food waste valorisation options, for UFW, based upon the parameters outlined above. This framework is then applied empirically via a case study with a major UK fruit consolidator to compare two different options for the valorisation of citrus waste residues. The results are analyzed not only in terms of their economic, environmental, social and technological performance as well as alignment with company goals, but also in terms of sensitivity to long term supply chain changes and possible impacts on supply chain partners. The paper finishes with discussions surrounding the strengths and limitations of the framework and suggestions for future work.

2. Review methodology

The purpose of this review is to explore how others have applied various research methodologies to aid in the selection/evaluation of food waste valorisation techniques and to identify which of these techniques best meets the needs of the framework proposed in this paper. To facilitate this, the review was performed, initially in August 2018 and again in February 2019, and consisted of the search strings presented in Table 1 applied to the following databases: Google Scholar, Science Direct, Wiley Online, Emerald and Scopus. These search strings were initially established based upon the authors own knowledge and were then refined through discussion with colleagues and project advisory/industrial partners. When using the search strings in databases, the primary phrase (i.e. 'Food Waste Valorisation') was combined exhaustively with each of the secondary phrases and each of the tertiary phrases and applied against article abstracts and titles. To be selected, an article had to match each word in each phrase somewhere within the title/abstract (although order was not important), for example, 'Food', 'Waste', 'Valorisation', 'Economic' and 'Analysis'. Only English language items which were peer reviewed (or from credible sources such as well cited books or government institutes) were selected. Whilst no date of publication restrictions were put in place, older works were carefully assessed for outmodedness before inclusion. Whilst not intended to be systematic, this approach was felt to be sufficiently broad and thorough that once the authors had read paper abstracts and duplicates were excluded, the final review size of 43 articles (listed in the supplementary materials document) is considered to reflect the state of the art in this research field.

3. Review findings

In this section, the 43 reviewed articles are categorized according to which methodological approach they employ. Approaches used include Life Cycle Assessment (LCA), Life Cycle Sustainability Assessment (LCSA), Life Cycle Costing (LCC), Cost-Benefit Analysis (CBA), Full Cost Accounting (FCA) and Variations on Multi-Criteria Decision Analysis (MCDA). Findings are described before being evaluated based on their suitability for capturing the aforementioned economic, environmental, social, technological maturity and alignment with company goal indicators as well practicality for an SME to implement.

3.1. Life Cycle Assessment

Life Cycle Assessment (LCA) is based upon the understanding that products in today's globalized markets will have environmental impacts at all stages of their life cycle, from production/extraction to processing, consumer use and end of life disposal, something that is often referred to as "cradle to grave". The aim of LCA is to measure these impacts and identify hotspots and opportunities for improvement without simply shifting the environmental burden to a different stage of the supply chain. This is typically achieved via four stages, beginning with the description of the goal and scope (including defining what is being compared, which processes are to be included and what the functional unit will be), inventory analysis (i.e. measurement of the inputs and outputs for each process), life cycle impact assessment (i.e. conversion of inventory items to common units for comparison) and interpretation (i.e. comparison of findings to make recommendations for intervention) (Cristóbal et al., 2018; Hellweg and i Canals, 2014; Hauschild et al, 2018). There are a wide range benchmarks for databases, such as ecoinvent, as well as methodologies to guide impact assessment (such as the International Reference Life Cycle Data System method) and even tools which can facilitate the entire LCA process (such as SimaPro and Gabi amongst many more). Furthermore the aforementioned tools and guidelines are tightly governed by international standards, most importantly ISO 14040:2006 and 14044:2006, as well as the International Reference Life Cycle Data System (ILCD) Handbook (Wolf et al., 2012) making LCA a respected and relatively accessible potential screening technique for SMEs.

In the context of food waste valorisation, a common approach is to use LCA to compare the environmental impacts of two or more different scenarios, with common examples being anaerobic digestion and animal feed (Vandermeersch et al., 2014; Salemdeeb et al., 2017).

Table 1
Review key words and search strings.

Primary Phrase	Secondary Phrases	Tertiary Phases
Food Waste Valorisation	Economic OR Cost Benefit OR Viability OR Technological OR Sustainability OR Environmental OR Social OR System	Analysis OR Modelling OR Evaluation

However, LCA has been applied to more diverse valorisation scenarios, such as ethanol manufacturing, production of value-added chemicals, and in a number of sectors such as beverage manufacturing (e.g. brewing (Amienyo and Azapagic, 2016; Guerrero and Muñoz, 2018; Lam et al., 2018)). In all cases, the goal is to identify and evaluate the most relevant indicator scores and compare them to the current (baseline scenario), to aid selection of a valorisation strategy. Often, impact assessment methods are used to transform mid-point indicators (e.g. global warming) into themes of particular interest to the user, such as damage to human health or damage to ecosystems, known as end-point indicators (Brunklaus et al., 2018). However, there are a number of potential limitations for effective use of LCA from the perspective of a food and drink manufacturer trying to select a valorisation process. The first is that whilst in principle, all stages of a food products life cycle should be considered and all possible environmental inputs/outputs should be considered for each stage, these data may not be readily available from supply chain partners. Additionally, LCA by nature only considers environmental impact, not social, economic, technological or company goals. As such, it does not have an inbuilt mechanism for identifying alternatives and is predominantly focused on identifying areas for improvement within a system rather than what a food a drink manufacturer could do instead with their waste. However, there are variations on LCA, such as Life Cycle Sustainability Analysis, which do cover some of these impacts.

3.2. Life Cycle Sustainability Assessment

Life Cycle Sustainability Assessment (LCSA) seeks to extend LCA principles of measuring the environmental life cycle impact of a product to include impacts on people and prosperity. In doing so, it brings LCA in line with the 1987 Bruntland report "triple bottom line" definition of sustainability, typically by including aspects of Life Cycle Costing (LCC) and Social Life Cycle Assessment (SLCC) (WCED, 1987. However, LCSA is broader than simply measuring additional social and economic impacts in that it broadens the level of analysis from impacts associated with a specific product to those associated with a specific sector or even economy (Guinée, 2016). It also aims to assess impact in more than just a technical sense, and therefore in addition to assessing, for example, process emissions, it also promotes the consideration of resource availability and relations between different companies in the supply chain. A such, rather than being a standarised method like LCA, LCSA can be thought of more as a framework for how to integrate various other models (e.g. LCA + LCC + SLCA).

There are a number of authors who can be considered to have applied one or more LCSA tenets to selection of food waste valorisation strategies. For example, San Martin et al., 2016 explore the suitability of vegetable waste produced by food industry for use as animal feed. This study analyzed all food wastes produced throughout the Basque country, analyzing each waste stream for potential impacts on health, LCA of the environmental impacts associated with processing each to animal feed and finally, technical feasibility via means of a pilot study. Salemdeeb et al. (2017) also explored the use of food waste as pig feed, this time in the UK, using a hybrid consequential/input-output LCA with normalized environmental and human health indicators to compare four scenarios: a) conversion into dry pig feed, b) conversion into wet pig feed, c) anaerobic digestion, and d) composting. In this scenario, conversion of food waste to wet pig feed presented the best outcomes both from and environmental and health perspective. Reich (2005) combines LCA with an economic and subsequent environmental LCC in order to assign weighted cost and environmental impact values to several options for valorising municipal waste including incineration, anaerobic digestion, composting and landfill with somewhat inconclusive results. Whilst LCSA has the potential to capture the full range of environmental, social, economic, technological and company fit indicators that would be required by a company attempting to identify their optimal waste valorisation process, there are still a number of limitations. First and foremost is the need for standarised and quantitative indicates for measuring social, technological and relational impacts (Guinee et al., 2010. Secondly, there is a real need for homogenous guidelines (as exist for LCA) which a company could follow to implement this process (Cinelli et al., 2013).

3.3. Life Cycle Costing

The aim of Life Cycle Costing (LCC) is to calculate the overall cost in monetary terms alone (as opposed to multidimensional impact as described previously for LCA/LCSA) of a product over its life cycle. There are a number of different variations, with Conventional LCC (C-LCC) perhaps being the most common (De Menna et al., 2016). C-LCC only concerns the costs borne internally by the company doing the analysis (to the exclusion of other value chain stages). Such costs are typically broken down into Initial Investment Costs (such as planning, design, site acquisition, construction, purchase and installation), Operating Costs (such as maintenance, repairs, energy, water, taxes and insurance) and Resale/Disposal costs (inspections, demolition and taxes) (Kim et al., 2011; De Menna et al., 2018). A more recent variant, known as Environmental Life Cycle Costing (E-LCC) is designed to link LCC and LCA by assigning monetary values to the impact factors explored in a parallel LCA (Swarr et al., 2011). For instance, Daylan and Ciliz (2016) used an E-LCC/CBA combination to analyze the valorisation of wheat straw waste to bioethanol demonstrating a 47% reduction in greenhouse gases combined with 56% lower production costs albeit at a higher risk of eutrophication and photochemical ozone depletion. However, the process by which monetary values are assigned to environmental impacts is not always straightforward and has been called into question by many (Guinée, 2016; San Martin et al., 2016; Reich, 2005; Guinee et al., 2010; Cinelli et al., 2013; De Menna et al., 2016, 2018; Kim et al., 2011; Swarr et al., 2011; Daylan and Ciliz, 2016; Martinez-Sanchez et al., 2016). Moving beyond E-LCC, a further development is Societal LCC (S-LCC) which involves the costs borne by all stages of society in relation to a given project. In principle, S-LCC is the most comprehensive costing technique identified in this review - albeit one that is in its infancy and still very poorly defined methodologically (Martinez-Sanchez et al., 2016). As a result of the complexities in interpreting and applying findings from all types of LCC, particularly E-LCC and S-LCC, many authors have highlighted how, as a methodology, it is best suited for deciding how to implement a valorisation process, in the most efficient way, which has already been chosen rather than as a means of comparing processes in the first instance (De Menna et al., 2016).

3.4. Cost-Benefit Analysis

The purpose of Cost-Benefit Analysis (CBA) is slightly different to LCC, in that it sets out to compare the net benefits of multiple potential strategies, rather than focusing on finding the most cost-effective way of implementing a predetermined strategy. These costs and benefits can be financial, social or environmental provided a common currency can be found and that they can be reasonably internalized by the company doing the CBA (Jamasb and Nepal, 2010; Benis et al., 2018; Lee et al., 2017). Just like LCC, costs/benefits are typically clustered around initial set up costs (i.e. building construction, equipment purchases), running costs (e.g. energy, labour) and end of life costs (e.g. decommissioning and waste disposal) (Demichelis et al., 2018; Tesfaye et al., 2018; Christoforou et al., 2016). These costs are then balanced against the projected market value of the products for each estimated year of the project life, and then discounted to take into account the typical higher industry preference for immediate return on investment (ROI) providing the Net Present Value (NPV) and Benefit-Cost Ratio (BCR) (Dimou et al., 2016).

The larger these are, typically, the more reliable a given project is. In this way, Arora et al. (2018) calculate that pectin and seed oil

extraction from mango waste (currently sent to landfill in India with no value) could generate an NPV of $43.2 million. Once NPV has been calculated, the CBA process is typically followed by a sensitivity analysis which takes into account a variety of factors which may influence costs and benefits over the project lifespan. These may include seasonal changes in feedstock availability or variation in market demand and are a good way of identifying potential risks. For example, Kwan et al. (2015) identified that, out of all possible variables, fluctuations in lactic acid price would have the biggest impact on project viability. Where multiple risk sources are identified, a typical response would be to increase the discount rate substantially, effectively only going ahead with projects that provided the fastest payoff, so as to reduce exposure to risk (Arora et al., 2018).

3.5. Full Cost Accounting

Full Cost Accounting (FCA), like CBA, enables the monetary valuation of social and environmental costs/benefits as well as financial costs. However, unlike CBA, the taxonomies of environmental, social and financial costs are not limited to internal costs and can therefore consider cost borne by other companies. The FCA methodology also differs from LCC in that the assignment of monetary values to indicators is not necessarily based on market prices and can be based on, for example, willingness to pay. One example is the 2014 Food Wastage Footprint Final Report from the FAO (Food and Agriculture Organization (FAO), 2014). This report calculated that global food waste annually accounted for $695 billion in environmental impacts on the atmosphere, water, soil and biodiversity, $882 billion in social impacts concerning livelihood loss, wellbeing loss, pesticide poisoning and conflict, as well as $1055 billion in direct financial losses. However, whilst increasingly established, such valuations of environmental and social costs are still challenging for a company to internalize making FCA more appropriate for national scale investigation by NGOs and Governments (Liu and Opdam, 2014; Liu et al., 2010).

3.6. Multi-Criteria Decision Analysis

Multi-Criteria Decision Analysis (MCDA) refers to a wide range of methods used to rank and compare multiple indicators of value to the user across multiple scales. There are a number of approaches which include distance functions (selection of indicators which are as far away from a predefined undesirable reference point as possible), outranking (an indicator is selected if it is at least as good as its nearest competitor), hierarchical (indicators are assigned a place in a hierarchy and assessed pairwise for prioritization) and weighted summation approaches (value for different scales of indicators are normalized, weighted and summed to rank options) (Diaz-Balteiro et al., 2017). Whilst not as commonly applied in the study of food waste valorisation as other techniques such as LCA, the most common MCDA approaches appear to be the hierarchy and weighted summation-based approaches. For example, Iacovidou and Voulvoulis (2018) utilize a weighted summation variant of MCDA in order to compare social, environmental and economic impacts of two different options for household food waste - anerobic digestion and on-site grinding for release and treatment with other sewerage. Findings suggested that anaerobic digestion performed slightly better, with the authors highlighting that the strength of this method lies in its procedural simplicity, allowing easy normalization, integration and comparison of multiple scales of indicators (Iacovidou and Voulvoulis, 2018). However, they caution that the method is prone to errors in data entries and particularly weighting, because, if one indicator scores particularly high for a process compared to other processes, and the weighting happens to be high, then it can significantly distort the final rank. Kapepula et al. (2007) use a different MCDA variant, known as PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluations) which is an outranking approach. Through this, they are able to rank a series of possible food waste interventions in Dakar.

Table 2
Summary of which of the criteria for assessing a food waste valorisation process have been/can be included in each of the six methodologies observed in the literature review.

Analysis of a given food waste valorisation strategy based upon:	LCA	LCSA	LCC			CBA	FCA	MCDA
			C-LCC	E-LCC	S-LCC			
Economic Viability		X	X	X	X	X	X	X
Environmental Sustainability	X	X		X	X	X	X	X
Social Sustainability		X			X	X	X	X
Technological Maturity		X						X
Alignment with Company Goals		X						X

Advantages cited were ease of application and the fact that it does not matter whether the indicators are proportionate or of very different scales. However, a potential drawback is that results are not displayed in a clear hierarchy, the process is susceptible to rank reversal if new alternatives are introduced and there are no guidelines for weighting of indicators.

3.7. Implications of review findings

In summary, the methods identified from the literature to assess food waste valorisation options were LCA. LCSA, LCC, CBA, FCA and MCDA. This section assesses the level to which each of these methodologies incorporates, or has the capacity to incorporate, the five parameters outlined in the introduction (summarized in Table 2). To recap, these were: economic viability (i.e. costs vs benefits), environmental performance (e.g. emissions, effects on human health), societal impact (e.g. job creation, noise generation), technological maturity (e.g. readiness of technology for valorisation at a lab scale, market readiness for the product and potential of the required technology to integrate with existing company processes) and finally alignment with company goals (strategic alignment, brand image and fit with existing expertise). Some of the approaches modelled are better suited to providing a thorough assessment of a single group of indicators on a cradle to grave scale, for example, environmental or monetary cost indicators in LCA and LCC respectively. One way of getting around this would be to use LCSA or FCA which both have provisions to include all of the aforementioned indicators whilst still retaining the rigorous cradle to grave assessment of impact/cost.

However, these methods present their own challenges in the sense that they are not standarised methodologies, but instead are frameworks for a variety of different methods without consistent guidelines or indicators. Not only is this problematic in its own right, for a company to pick up and apply when they may not have expertise in sustainability modelling, or the time and ability to collect the necessary data, but the life cycle focus may be unnecessary at this scoping stage. This is because whilst a life cycle-based assessment is very important in selecting the best way of implementing a valorisation pathway, it is not always necessary to initially select which out of many possible valorisation pathways are likely to be the best for a company. For example, if a company is looking for an alternative to their spoilt fruit within a factory, the initial need may well be simply to find out what valorisation processes are available and for each, to identify the cost of a process (set up, running and end of life), the immediate environmental impact (emissions to land air and water), social impact (jobs created and noise) technological readiness (i.e. is the process ready to install at an industrial level and is the market ready for the output) and finally its impact with company goals (e.g. does the product of valorisation fit our brand image).

Whilst it could reasonably be claimed that a company could simply adjust the scope and boundaries of their LCSA to achieve this, other techniques such as the Weighted Summation or Outranking MCDA variants may be more appropriate given that they are typically faster, simpler and avoid some of the challenges of conversion of different indicator scales to common units. In particular, for a company considering many potential criteria, the weighted summation method offers the simplest rank hierarchy, being easy to assign weights to and without risk of rank reversal. That is not to say that life cycle-based approaches are not relevant and certainly, once a company has selected the best valorisation process for their bespoke situation via screening, the goal would then switch to optimal implementation of that process and this is where wider life cycle impacts become more relevant. For example, if a company identified through such a screening process that the optimal way of valorising their spoilt fruit was to send it to a nearby farm for anaerobic digestion, then consideration of wider goals such as costs of environmental impacts, social impacts and financial costs associated with transport, activities on the farm and ultimate use of the outputs including energy and digestate would need to be considered to ensure anerobic digestion was performed in the most sustainable way. However, that level of detail would not have been necessary to initially identify and compare the scenarios that were most viable for that company. For this reason, the weighted summation variant of MCDA was chosen as the basis for the pragmatic framework presented in this paper. It is appreciated that a downside to this variant is that there is large amount of freedom provided to users to select indicators for use and weightings assigned, meaning that the outcome scores may not accurately represent the situation in reality. In an attempt to mitigate this, it was decided that the framework would incorporate the widest possible range of relevant indicators for food and drink manufacturers, as suggested by the literature, that equal weighting would be strongly recommended and that collection of data for these indicators would be based on empirical techniques, namely LCA and CBA. The formation of the pragmatic framework and the integration of the MCDA, LCA and CBA techniques is now described in detail.

4. Pragmatic framework development

This section presents a Sustainable Waste Valorisation Identifier 'SWaVI' for the UK Food and Drink Sector. Its goal is to enable companies of any size to identify and compare different strategies for valorising Unavoidable Food Waste (UFW), based on economic, environmental and social impact, technological readiness and fit with company goals. To achieve this, SWaVI is composed of five stages as summarized below in Fig. 1.

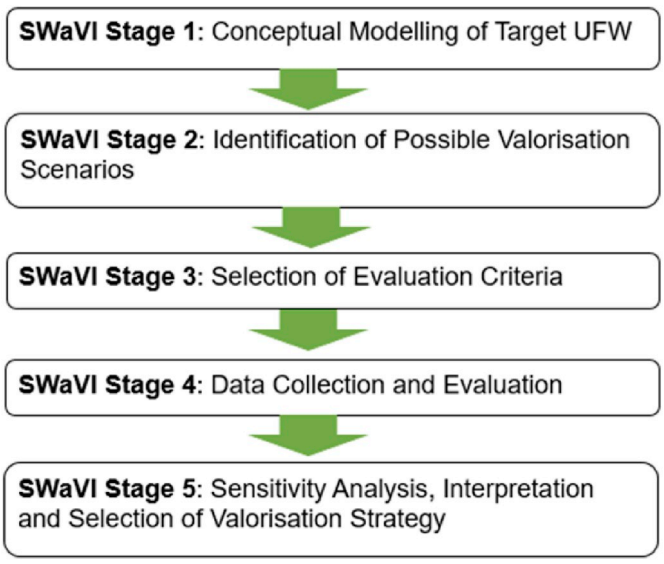


Fig. 1. Pragmatic framework overview.

4.1. SWaVI stage 1: conceptual modelling of target unavoidable food waste

The first stage concerns the modelling of where in a company's operations UFW is created, to what volumes and timescales it is created and what relevant legislation and wider stakeholder interests are involved (Fig. 2).

This stage begins by identifying the value chain boundaries of UFW, for example, if a company is involved in some primary production in addition to processing, is UFW considered in one or both stages? The next step is to fully model the processes which lead to waste production in the selected stages, considering the volumes that are produced, their chemical composition, and the timescale of this production (e.g. how much is produced hourly/daily/monthly and are there any fluctuations over time?). Having identified exactly where the waste originates, the next step is to identify what relevant legislation applies to that particular UFW stream, broadly speaking, in terms of permitting, taxes and what relevant financial incentives might be available. At this stage, it is also important for a company to consider whether there are any value chain partners who are indirectly dependent on the UFW in questions, for example, if local farmers are collecting a waste for use as a free animal feed, what would they do if this supply became unavailable? Identifying and modelling UFW streams in this way is a fundamental prerequisite for identifying realistic potential valorisation scenarios in Stage 2 of the framework, and subsequently relevant assessment criteria in Stage 3.

4.2. SWaVI stage 2: identification of possible valorisation scenarios

The second framework stage involves the identification of realistic potential valorisation scenarios based on the waste stream characteristics in the first stage of the framework. For any UFW stream, there will be multiple possible valorisation scenarios depending upon factors such as seasonality, chemical composition and market demand. Table 3 provides initial guidance on potential valorisation scenarios for a number of key food commodities (based on the Agrocycle database, 2016) and their main UFW streams based on their volumes and seasonality (Patsios et al., 2017). As can be seen, many waste streams have potential for anaerobic digestion, or use as fertilizer or animal feed, typically requiring low initial investment from a company, but also resulting in small, if any, financial return thus making them best suited when the goal is simply a more sustainable form of disposal (Selection Code A in Table 3). It should also be noted that policy legislation, such as tax breaks on the Climate Change Levy (CCL) and whether anaerobic digestion takes place as part of a certified Combined Heat & Power (CHP) system, could potentially make such valorisation scenarios more profitable than they would initially seem (UK Government, 2019).

Certain foods also have characteristics, such as high cellulose content, which make them ideally suited for conversion to bioethanol, attracting a potentially higher value, but also potentially incurring significant transport distances, a high environmental impact, and variable returns depending on fossil fuel market performance (i.e. the cheaper fossil fuel is, the lower the competitiveness of bioethanol). Given the complexity of setting up this process at scale, it is unlikely a company could perform this option outside of an independent biorefinery. However, the high environmental impact can be partially offset by combining this approach with anaerobic digestion of the residues left over from bioethanol production which may also generate revenue (Rocha-Meneses et al., 2017). Other waste streams possess unique valuable compounds that may be particularly valuable. At the same time, extraction, processing and marketing of these products may require high initial investment cost as well as year-round high-volume stable supplies of waste. By comparing these considerations with the composition, quantity and seasonality of their own waste, a company can

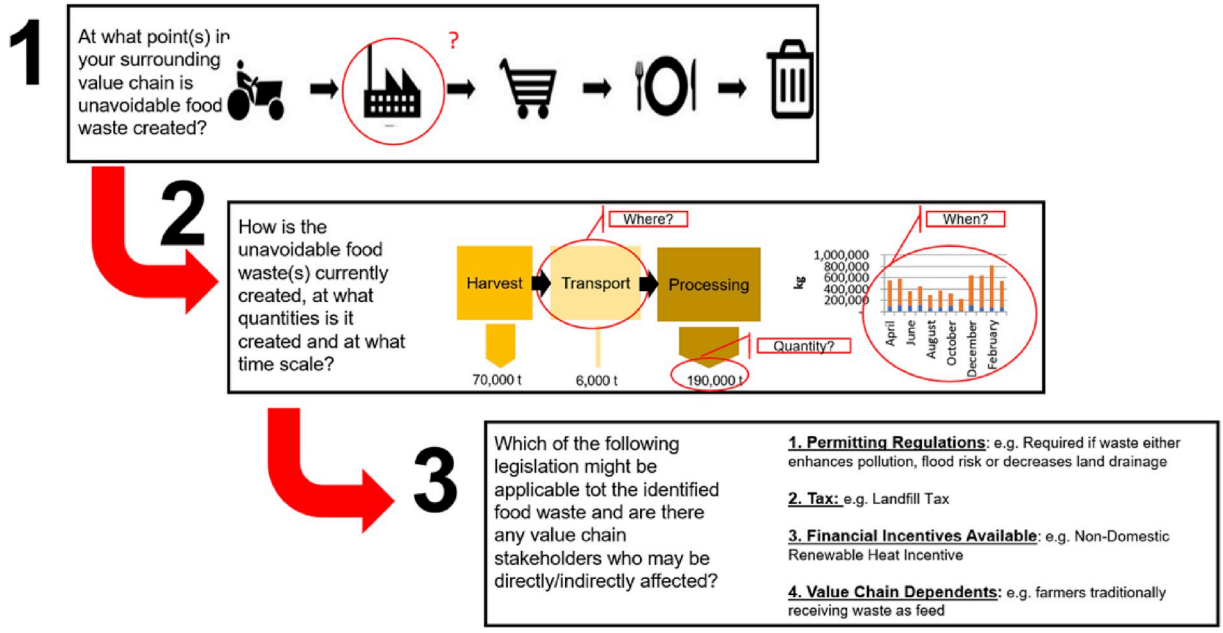


Fig. 2. The three stages involved in identifying an UFW source, delimiting the system boundaries, characterizing the UFW and identifying relevant policy/stakeholder considerations.

Table 3
Different valorisation scenarios for a variety of commonly occurring unavoidable food wastes. Selection codes refer to: a) Low value, to be used when either: i) ability to invest in valorisation is low or, ii) the goal is sustainable disposal rather than profit, b) Bioethanol has the potential for high value returns but requires year-round reliably high feedstock volumes, and the ability to offset potential transport costs and environmental impacts, c) Highest value but requires high volumes, stable annual production and significant capital investment. Compiled using data from the Agrocycle database, 2016.

Commodity	Main Internal Associated UFW	Potential Valorisation Scenario	Selection Code
Milk (Cow)	Whey waste water	Drying for animal feed	A
		Use as fertilizer	A
		Processing for human consumption (e.g. whey powder, lactose, cheese)	C
		Production of bioethanol	B
		Anaerobic digestion	A
Grains	Bran	Drying for animal feed	A
		Extraction of components for human consumption (e.g. protein, oil, starch)	C
		Production of bioethanol	B
		Anaerobic digestion	A
Potatoes	Peels	Extraction of valuable compounds for human consumption (e.g. starch)	C
		Anaerobic digestion	A
Sugar beet	Molasses	Drying for animal feed	A
		Extraction of valuable compounds (particularly minerals)	C
		Production of bioethanol	B
Grapes	Pomace	Drying for animal feed	A
		Extraction of valuable compounds for human consumption	C
		Anaerobic digestion	A
Tomatoes	Peels	Drying for animal feed	A
		Extraction of valuable compounds (e.g. lycopene)	C
Olives	Pomace	Drying for animal feed	A
		Extraction of valuable compounds for human consumption	C
Oilseeds	Cake	Drying for animal feed	A
		Extraction of components for human consumption (e.g. pectin, essential oils)	C
		Anaerobic digestion	A
Apples	Pomace	Drying for animal feed	A
		Extraction of valuable compounds (e.g. pectin)	C
Citrus	Pomace/Peels	Drying for animal feed	A
		Extraction of valuable compounds (e.g. pectin, limonene)	C
Onions	Peels	Anaerobic digestion	A
		Extraction of valuable compounds (particularly dietary fiber, flavonoids and S-alk(en)yl-L-cysteine sulfoxide	C
Rice	Husk/bran	Drying for animal feed	A
		Extraction of valuable compounds for human consumption	C
		Anaerobic digestion	A
Meat/Fish	Trimmings/Bones	Anaerobic digestion	A

Table 4
Evaluation criteria taxonomy.

Type of criteria	Sub-Criteria	Units	Reference
Economic Viability	Raw Material Cost (RMC)	£/ton	(Kim et al., 2011; De Menna et al., 2018; Swarr et al., ; Daylan and Ciliz, 2016; Martinez-Sanchez et al., 2016; Jamasb and Nepal, 2010; Benis et al., 2018; Lee et al., 2017; Demichelis et al., 2018; Tesfaye et al., 2018; Christoforou et al., 2016; Dimou et al., 2016; Arora et al., 2018; Food and Agriculture Organization (FAO), 2014; Liu and Opdam, 2014; Liu et al., 2010; Kapepula et al., 2007; Patsios et al., 2017; Environmental taxes and reli, 2019; Rocha-Meneses et al., 2017; Styles et al., 2016)
	Capital Costs (e.g. land/ equipment) (CC)	£/item	(Kim et al., 2011; De Menna et al., 2018; Swarr et al., ; Daylan and Ciliz, 2016; Martinez-Sanchez et al., 2016; Jamasb and Nepal, 2010; Benis et al., 2018; Lee et al., 2017; Demichelis et al., 2018; Tesfaye et al., 2018; Christoforou et al., 2016; Dimou et al., 2016; Arora et al., 2018; Food and Agriculture Organization (FAO), 2014; Liu and Opdam, 2014; Liu et al., 2010; Kapepula et al., 2007; Patsios et al., 2017; Environmental taxes and reli, 2019; Rocha-Meneses et al., 2017; Styles et al., 2016)
	Operational & Maintenance Costs (e.g. depreciation, repairs, labor) (OMC)	£/hour	(Kim et al., 2011; De Menna et al., 2018; Swarr et al., ; Daylan and Ciliz, 2016; Martinez-Sanchez et al., 2016; Jamasb and Nepal, 2010; Benis et al., 2018; Lee et al., 2017; Demichelis et al., 2018; Tesfaye et al., 2018; Christoforou et al., 2016; Dimou et al., 2016; Arora et al., 2018; Food and Agriculture Organization (FAO), 2014; Liu and Opdam, 2014; Liu et al., 2010; Kapepula et al., 2007; Patsios et al., 2017; Environmental taxes and reli, 2019; Rocha-Meneses et al., 2017; Styles et al., 2016)
	Sales Revenue (both primary and by/co-products) (SR)	£/item or ton	(Kim et al., 2011; De Menna et al., 2018; Swarr et al., ; Daylan and Ciliz, 2016; Martinez-Sanchez et al., 2016; Jamasb and Nepal, 2010; Benis et al., 2018; Lee et al., 2017; Demichelis et al., 2018; Tesfaye et al., 2018; Christoforou et al., 2016; Dimou et al., 2016; Arora et al., 2018; Food and Agriculture Organization (FAO), 2014; Liu and Opdam, 2014; Liu et al., 2010; Kapepula et al., 2007; Patsios et al., 2017; Environmental taxes and reli, 2019; Rocha-Meneses et al., 2017; Styles et al., 2016)
	Utilities Cost (e.g. energy and water) (UC)	£/unit	(Kim et al., 2011; De Menna et al., 2018; Swarr et al., ; Daylan and Ciliz, 2016; Martinez-Sanchez et al., 2016; Jamasb and Nepal, 2010; Benis et al., 2018; Lee et al., 2017; Demichelis et al., 2018; Tesfaye et al., 2018; Christoforou et al., 2016; Dimou et al., 2016; Arora et al., 2018; Food and Agriculture Organization (FAO), 2014; Liu and Opdam, 2014; Liu et al., 2010; Kapepula et al., 2007; Patsios et al., 2017; Environmental taxes and reli, 2019; Rocha-Meneses et al., 2017; Styles et al., 2016)
	Government Subsidies/ Incentives (GSI)	£/unit of capacity	(Kim et al., 2011; De Menna et al., 2018; Swarr et al., ; Daylan and Ciliz, 2016; Martinez-Sanchez et al., 2016; Jamasb and Nepal, 2010; Benis et al., 2018; Lee et al., 2017; Demichelis et al., 2018; Tesfaye et al., 2018; Christoforou et al., 2016; Dimou et al., 2016; Arora et al., 2018; Food and Agriculture Organization (FAO), 2014; Liu and Opdam, 2014; Liu et al., 2010; Kapepula et al., 2007; Patsios et al., 2017; Environmental taxes and reli, 2019; Rocha-Meneses et al., 2017; Styles et al., 2016)
	Net Present Value (sum of all of the above + discounting) (NPV)	£	(Kim et al., 2011; De Menna et al., 2018; Swarr et al., ; Daylan and Ciliz, 2016; Martinez-Sanchez et al., 2016; Jamasb and Nepal, 2010; Benis et al., 2018; Lee et al., 2017; Demichelis et al., 2018; Tesfaye et al., 2018; Christoforou et al., 2016; Dimou et al., 2016; Arora et al., 2018; Food and Agriculture Organization (FAO), 2014; Liu and Opdam, 2014; Liu et al., 2010; Kapepula et al., 2007; Patsios et al., 2017; Environmental taxes and reli, 2019; Rocha-Meneses et al., 2017; Styles et al., 2016)
Environmental Sustainability	Energy, Water and Mineral Efficiency (EWME)	Volume consumed/ton product	(Vandermeersch et al., 2014; Salemdeeb et al., 2017)
	Climate Change Potential (CCP)	kg CO_2-eq.	(Vandermeersch et al., 2014; Salemdeeb et al., 2017; Amienyo and Azapagic, 2016)
	Human Toxicity Potential (HTP)	CTUh/mPE year	(Vandermeersch et al., 2014; Salemdeeb et al., 2017)
	Photochemical Ozone Formation Potential (POFP)	kg NMVOC eq	(Vandermeersch et al., 2014; Salemdeeb et al., 2017; Amienyo and Azapagic, 2016)
	Acidification Potential (AP)	AE/mPE year	(Vandermeersch et al., 2014; Salemdeeb et al., 2017; Amienyo and Azapagic, 2016)
	Eutrophication Potential (EP)	kg N eq./mPE year	(Vandermeersch et al., 2014; Salemdeeb et al., 2017; Amienyo and Azapagic, 2016)
	Ozone Depletion Potential (ODP)	kg CFC-11-eq./mPE year	(Vandermeersch et al., 2014; Salemdeeb et al., 2017; Amienyo and Azapagic, 2016; Guerrero and Muñoz, 2018; Lam et al., 2018; Brunklaus et al., 2018; Our, 1987; Guinée, 2016; San Martin et al., 2016; Reich, 2005; Guinee et al., 2010; Cinelli et al., 2013; De Menna et al., 2016; Kim et al., 2011; De Menna et al., 2018; Swarr et al, 2011; Daylan and Ciliz, 2016; Martinez-Sanchez et al., 2016; Jamasb and Nepal, 2010; Benis et al., 2018; Lee et al., 2017; Demichelis et al., 2018; Tesfaye et al., 2018; Christoforou et al., 2016; Dimou et al., 2016; Arora et al., 2018; Food and Agriculture Organization (FAO), 2014; Liu and Opdam, 2014; Liu et al., 2010; Kapepula et al., 2007; Patsios et al., 2017; Environmental taxes and reli, 2019; Rocha-Meneses et al., 2017; Styles et al., 2016; Lundie and Peters, 2005; Parfitt et al., 2016b; WRAP, 2014)
	Ecotoxicity Potential (EP)	CTUe/mPE year	(Vandermeersch et al., 2014; Salemdeeb et al., 2017; Amienyo and Azapagic, 2016; Guerrero and Muñoz, 2018; Lam et al., 2018; Brunklaus et al., 2018; Our, 1987; Guinée, 2016; San Martin et al., 2016; Reich, 2005; Guinee et al., 2010; Cinelli et al., 2013; De Menna et al., 2016; Kim et al., 2011; De Menna et al., 2018; Swarr et al., 2011; Daylan and Ciliz, 2016; Martinez-Sanchez et al., 2016; Jamasb and Nepal, 2010; Benis et al., 2018; Lee et al., 2017; Demichelis et al., 2018; Tesfaye et al., 2018; Christoforou et al., 2016; Dimou et al., 2016; Arora et al., 2018; Food and Agriculture Organization (FAO), 2014; Liu and Opdam, 2014; Liu et al., 2010; Kapepula et al., 2007; Patsios et al., 2017; Environmental taxes and reli, 2019; Rocha-Meneses et al., 2017; Styles et al., 2016; Lundie and Peters, 2005; Parfitt et al., 2016b; WRAP, 2014)
	Land Use Change (LUC)	m^2a	(Vandermeersch et al., 2014; Salemdeeb et al., 2017; Amienyo and Azapagic, 2016; Guerrero and Muñoz, 2018; Lam et al., 2018; Brunklaus et al., 2018; Our, 1987; Guinée, 2016; San Martin et al., 2016; Reich, 2005; Guinee et al., 2010; Cinelli et al., 2013; De Menna et al., 2016; Kim et al., 2011; De Menna et al., 2018; Swarr, et al., 2011; Daylan and Ciliz, 2016; Martinez-Sanchez et al., 2016; Jamasb and Nepal, 2010; Benis et al., 2018; Lee et al., 2017; Demichelis et al., 2018; Tesfaye et al., 2018; Christoforou et al., 2016; Dimou et al., 2016; Arora et al., 2018; Food and Agriculture Organization (FAO), 2014; Liu and Opdam, 2014; Liu et al., 2010; Kapepula et al., 2007; Patsios et al., 2017; Environmental taxes and reli, 2019; Rocha-Meneses et al., 2017; Styles et al., 2016; Lundie and Peters, 2005; Parfitt et al., 2016b; WRAP, 2014)

(*continued on next page*)

Table 4 (*continued*)

Type of criteria	Sub-Criteria	Units	Reference
Social Sustainability	Social Acceptability (SA)	+ + / –	(Chong et al., 2016; Den Boer et al., 2007)
	Odors Generation (OG)	+ + / –	Den Boer et al. (2007)
	Noise Creation (NC)	dB	(Den Boer et al., 2007; Kythreotou et al., 2014; European Commission.(BAT), 2019; Den Boer, Brouwer, Schroten, Van Essen)
	Job Creation (JC)	number of people benefitted/ ton	(Den Boer et al., 2007; Kythreotou et al., 2014; European Commission.(BAT), 2019; Den Boer, Brouwer, Schroten, Van Essen; Buksti et al., 2015)
	Traffic Generation (TG)	Number of vehicles/ton of FW	(Den Boer et al., 2007; Kythreotou et al., 2014; European Commission.(BAT), 2019; Den Boer, Brouwer, Schroten, Van Essen; Buksti et al., 2015; Kijak and Moy, 2004)
Technological Maturity	Technology Readiness Level (TRL)	1-9 (1 = basic principles observed, 9 = actual system proven)	(N 2020—Work Program, 2014; Solberg Hjorth and Brem, 2016)
	Integration Readiness Level (IRL)	1-7 (1 = technologies can connect but not integrate, 7 = seamless integration)	(Solberg Hjorth and Brem, 2016; Sauser et al., 2006)
	Demand Readiness Level (DRL)	1-9 (1 = feeling something is missing, 9 = completed answer to actual need of market)	(Solberg Hjorth and Brem, 2016; Sauser et al., 2006; Paun)
Alignment with Company Goals	Fit with Strategy (FS)	1-5 (1 = poor, 3 = moderate, 5 = strong)	WRAP (2019)
	Fit with Brand Image (FBI)	1-5 (1 = poor, 3 = moderate, 5 = strong)	WRAP (2019)
	Fit with Company Expertise (FCE)	1-5 (1 = poor, 3 = moderate, 5 = strong)	WRAP (2019)

select the most appropriate valorisation strategies based on the waste characteristics and company goals generated in SWaVI Stage 1 and available valorisation scenarios outlined in SWaVI Stage 2. Once this has been achieved, the next step is to choose suitable criteria by which to evaluate them.

4.3. SWaVI stage 3: selection of evaluation criteria

In order to identify which of the shortlisted valorisation scenarios is best suited to the user, the different possibilities must be evaluated according to their economic, social, environmental, and brand image impact, as well as their technology readiness level. To achieve this, Table 4 presents a taxonomy of indicators compiled via the previously described review of the literature concerning assessment of food waste valorisation. All of the criteria displayed in Table 4 have been identified in the literature as being fundamental to sustainable valorisation of food waste and so should be of relevance to all food and drink manufacturers regardless of size or waste stream being evaluated. At a minimum, the criteria in Table 4 would be applied to the direct impacts generated by a company when valorising their food waste in a given way, for example, direct emissions, building costs and noise generation associated with a new process to extract valuable compounds from food waste. In certain scenarios, waste may be sent to a third party for valorisation, for example, anaerobic digestion on a nearby farm and in this case, the user should apply the criteria from Table 4 to that third party to avoid externalization of impact.

4.4. SWaVI stage 4: data collection and evaluation

Stage 4 of the SWaVI framework describes the collection of relevant data for each of the evaluation criteria identified in Stage 3 and the process by which that data are analyzed. To facilitate data collection, the evaluation criteria selected in SWaVI Stage 3 should be categorized in an evaluation matrix and values for each recorded (see Table 5 for an example). Measurements should be precise and recorded per ton of waste valorised, using the units listed in Table 4.

In this way, a Cost-Benefit Analysis is performed to generate the Net Present Value of each scenario, a Life Cycle Assessment is used to generate each of the environmental values and consultation with internal process managers and where necessary external stakeholders is performed to generate, social, technological maturity and alignment with company goals indicators. For full details of the recording and analysis processes in a real-world example, please review the supplementary material document (Section 2). The example evaluation matrix in Table 5 highlights that when completed in this way, the scales of the different evaluation criteria are very different and cannot be directly compared. To overcome this, the weighted summation method (WSM), as described by Herwijnen (2006) is applied to the values recorded in the evaluation matrix (Herwijnen, 2006). In the weighted summation approach, each of the evaluation criteria and their sub-criteria have their units removed and are standarised based upon their position in relation to the highest and lowest recorded values for that criteria which is expressed on a scale of 0–1. This is described in Equation (1) used for non-beneficial criteria (e.g. environmental pollution) and Equation (2) for beneficial criteria (job creation). In both equations, Vi = the standardized value for a given evaluation criterion (i) and Sij = the original score for evaluation criterion i under valorisation option j.

$$Vi = \frac{\min Sij}{Sij} \tag{1}$$

$$Vi = \frac{Sij}{max\ Sij} \tag{2}$$

The standardized values for each evaluation criterion and sub-criterion are then assigned a weight. As all of the evaluation criteria are

equally essential in enabling sustainable valorisation of food waste, unless there is very good reason, an equal weighting method must be used (see Supplementary data, Table 4 for details). In this way, the standardized values for each of the evaluation sub-criteria can then be multiplied by their respective weightings and summed to give a total value for valorisation scenario as shown in Equation (3).

$$Score\ (j) = \sum_{Wi}^{N} WiVi \tag{3}$$

4.5. SWaVI stage 5: sensitivity analysis, interpretation and selection of valorisation strategy

The final section of the SWaVI framework describes the process for applying sensitivity analysis to explore how minor variations in the values of each of the evaluation criteria may alter the ranking of the valorisation scenarios. This is particularly important if the results for the valorisation scenarios being compared are very close, as it shows the evaluation criteria which are most sensitive to change and can be used as an indicator of risk.

However, even if the results for the valorisation scenarios are not close, sensitivity analysis can provide highly useful insights into areas of exposure, particularly from the wider supply network which may not have otherwise been considered in the selection of a given valorisation scenario. Having finished describing the SWaVI process, a case study application with a major UK fruit consolidator is now presented.

5. Case study

The case study application of the SWaVI framework was performed in collaboration with Chingford Fruit Ltd (referred to from now as “CF”). The purpose was solely to demonstrate the potential of the SWaVI framework and was not designed to guide CF in actually implementing a change in how they valorised their food waste. CF, part of A G Thames Holdings, is a large fresh fruit consolidator, specializing in the sourcing and packaging of citrus fruits, stone fruits, top fruits and kiwis from a large range of international sources and their subsequent supply to the UK wholesale and retail sectors. Their position, effectively as a screening point for fresh fruit entering the UK means that they produce large volumes of waste, a significant proportion of which is not fit for human consumption. This citrus waste is also rich in potential valuable compounds ranging from pectin to limonene and flavonoids making CF an ideal test scenario (Ciriminna et al., 2014). As such, the following sections correspond to application of each of the 5 SWaVI framework sections respectively. For conciseness, only the case study outcomes and implications are described in detail, the collection process and the data analysis procedures are described in detail in Section 2 of the supplementary data.

5.1. SWaVI stage 1: conceptual modelling of target unavoidable food waste

The first step in the conceptual modelling was to identify where in their value chain CF had control over waste generation, and if there were multiple waste streams, which would be the focus of valorisation efforts. As shown in Fig. 3, CF identified that they were responsible for managing waste in transit from the supplier (typically in containers via cargo ships) and within their facility in Dartford, UK, prior to dispatch to customers. As described previously, within this boundary, citrus fruit constituted by far the largest waste source and was the sole waste stream to be focused on in this case study. CF identified that on average (between 2013 and 2017) 4,399,834 kgs of citrus waste was generated a year. The majority of this, on average 3,459,967 kg annually, is in the form of ‘2nd class fruit’, in other words, fruit that is safe for human consumption, but which will not meet the quality standards of CF's customers. This waste originates primarily as a result of natural variation and environmental factors in the growing regions and whilst CF encourages high quality control in its suppliers, the low margin, high volume nature of the business means that such 2nd class fruits easily slip through. However, an average of 939,867 kg annually is not fit for human consumption due to serious damage or decomposition. Whilst exact figures on where this waste occurs are not available, it is thought to predominantly originate during transportation to CF and waste generation at CF is minimal due to careful packaging and temperature control. All 2nd class fruit is currently sent to wholesale market at a significantly lower price than they would receive from their intended customer (typically 80% lower). All uneatable waste is sent for anaerobic digestion at a net loss for CF. The results also highlight the seasonal nature of citrus waste production at CF. In some cases, obvious factors such as seasonal demand around the festive season drive waste in December/January. Others are less easy to predict, with the values for April being disproportionately influenced by particularly bad weather in supplier regions in April 2013 which severely impacted the cosmetic quality of the harvest. Finally, the interviews explored value chain stakeholders who might stand to lose if the way in which this waste stream was treated changed. The main stakeholders who would be affected by a change to management of uneatable waste are a local farm, Guy & Wright, who grow tomato plants for one of the UK's top supermarkets. Digestion of the waste generates enough thermal and electrical energy for the 3-acre farm to be completely self-sufficient and sustainable.

As the farm is the sole-recipient of CF's uneatable waste, this represents a significant volume of their input and whilst it is likely alternatives may be found, the transport distance would likely increase, thus decreasing the economic and environmental efficiency of this treatment option. Therefore, this has been ranked as a medium risk. With regard to legislation and the current management of citrus waste, as CF does not emit any of their waste to the environment, they are exempt from landfill tax and environmental permits. They are also small enough in operations that they could not apply for a reduction in climate change levy payments and current process are not eligible for capital allowances on energy-efficient equipment and so no legislative considerations were considered during this case study. SWaVI Stage 2 now describes how appropriate valorisation scenarios for this waste stream were identified.

5.2. SWaVI stage 2: identification of possible valorisation scenarios

Whilst the current method of managing 2nd class waste via wholesale, thus enabling human consumption, ranks high from a social and environmental perspective, it does represent a substantial economic loss of approximately 80% for CF. With this in mind, a number of valorisation options were considered (see Table 3). Anaerobic digestion and animal feed were discounted because the economic returns were likely to be lower than was already achieved through wholesale as 2nd fruit and because human consumption is superior to animal consumption and energy recovery on the waste hierarchy (Bampidis and Robinson, 2006). Consideration therefore turned toward the extraction of valuable compounds. Whilst citrus is well known for its cellulose and sugar content, the market value of cellulose and bioethanol that is derived from fermentation of sugar are both low. As a result, it was decided to focus on more valuable compounds, namely, pectin, an important stabilizer and thickening agent used by the food industry (John et al., 2017). Pectin is also a high-value material with prices averaging at $15 per kg and projected growth to $1.9 billion by 2025 due to growing global demand for healthy filling and thickening agents in food and increasingly medicine (Sharma et al., 2017; Ciriminna et al., 2016). A number of other factors besides economics also make pectin extraction an attractive proposal for CF. One is that whilst there is some seasonal variation in waste, overall, supply is continuous and relatively predictable each year. Another is that pectin extraction fits well with CF's brand image and market position as a major fresh fruits

Table 5
Example evaluation criteria data collection matrix.

Evaluation Criteria		Economic Viability	Environmental Sustainability		Social Sustainability		Technological Maturity		Alignment with Company Goals	
Sub-Criteria		e.g. Net Present Value	e.g. Climate change potential	e.g. photochemical ozone formation potential	e.g. noise	e.g. traffic	e.g. TRL	e.g. IRL	e.g. fit with brand image	e.g. fit with company strategy
Scenario	valuable compound extraction	£500,000	50 kg CO_2-eq	0.01 kg NMVOC eq	80 dB	3	7	3	5	5
	animal feed	£100,000	20 kg CO_2-eq	0.001 kg NMVOC eq	10 dB	1	8	5	3	1
	anaerobic digestion	£20,000	35 kg CO_2-eq	0.002 kg NMVOC eq	30 dB	1	9	7	3	1

consolidator and supplying pectin domestically, particularly with political events such as the departure of the UK from the European Union between 2019 and 2020, would likely allow CF to expand their food manufacturing customer base. From a technical perspective, whilst traditional pectin extraction methods are typically large scale and can be environmentally harmful, a number of recent developments using Microwave Assisted Pectin Extraction (MAPE) mean that set up costs are more viable for smaller companies and sustainability overall, is much higher (Maran et al., 2014; Eskilsson and Björklund, 2000). With the aforementioned considerations in mind, it was decided that comparison would take place between wholesale of 2nd class fruit and MAPE with data for this later process being collected from empirical research conducted at the University of York as described by Garcia-Garcia et al. (2019). SWaVI Stage 3 will now explore how indicators were identified for the assessment of the two selected valorisation scenarios.

5.3. SWaVI stage 3: selection of evaluation criteria

With regard to the economic criteria, the MAPE scenario would involve significant capital investment to purchase equipment as well as lifespan running costs and end of life costs associated with any residues. Therefore, Raw Material Cost (RMC), Capital Costs (CC), Operational & Maintenance Costs (OMC), Sales Revenue (SR), Utilities Cost (UC), and Government Subsidies/Incentives (GSI) were selected for inclusion. Additionally, a Cost-Benefit Analysis was performed on these criteria so as to generate a discounted Net Present Value which took into account the fact that returns in the present are generally preferred over those that would take a long time to be realized. Whilst it is clear that set-up costs for the wholesale scenario are much lower, there are still set-up and running costs associated and so these criteria were deemed suitable for both scenarios.

In terms of environmental evaluation criteria, it was identified that both the wholesale and the MAPE process had the potential to result in emissions to air, water and land for which CF would be responsible. Therefore, Climate Change Potential (CCP), Human Toxicity Potential (HTP), Photochemical Ozone Formation Potential (POFP), Acidification Potential (AP), Eutrophication Potential (EP), Ozone Depletion Potential, and Ecotoxicity Potential (EP) were identified for inclusion. Land Use Change (LUC) was not included as neither the MAPE process or wholesale of waste impacted on land use change. Additionally, whilst Energy, Water and Mineral Efficiency (EWME) was identified as being relevant, it was not included due to challenges in obtaining suitable data from CF.

In terms of social evaluation criteria, Social Acceptability (SA), Odor Generation (OG), Noise Creation (NC), Job Creation, (JC) and Traffic Generation (TG) were identified as being relevant to the MAPE scenario and wholesale scenarios alike. Likewise, with regard to technological maturity of each scenario, Technology Readiness Level (TRL), Integration Readiness Level (IRL) and Demand Readiness Level (DRL) were all identified as being appropriate due to the fact that MAPE, as a new process involved not only the use of new technologies, but also their integration with broader value chains and fit with market demand for a new product. Finally, in order to establish how well the MAPE scenario aligned with CF, Fit with Strategy (FS), Fit with Brand Image (FBI) and Fit with Company Expertise (FCE) were selected. For each of the aforementioned criteria, the boundaries for impact were delimited by where the valorisation scenario deviated from the normal procedure for disposal of that waste and were limited to direct impacts borne by CF. Full details on these boundaries can be found in the supplementary data document. In Stage 4 of the SWaVI framework, data collected for each of the selected evaluation criteria is analyzed using the approach set out in Section 4.4.

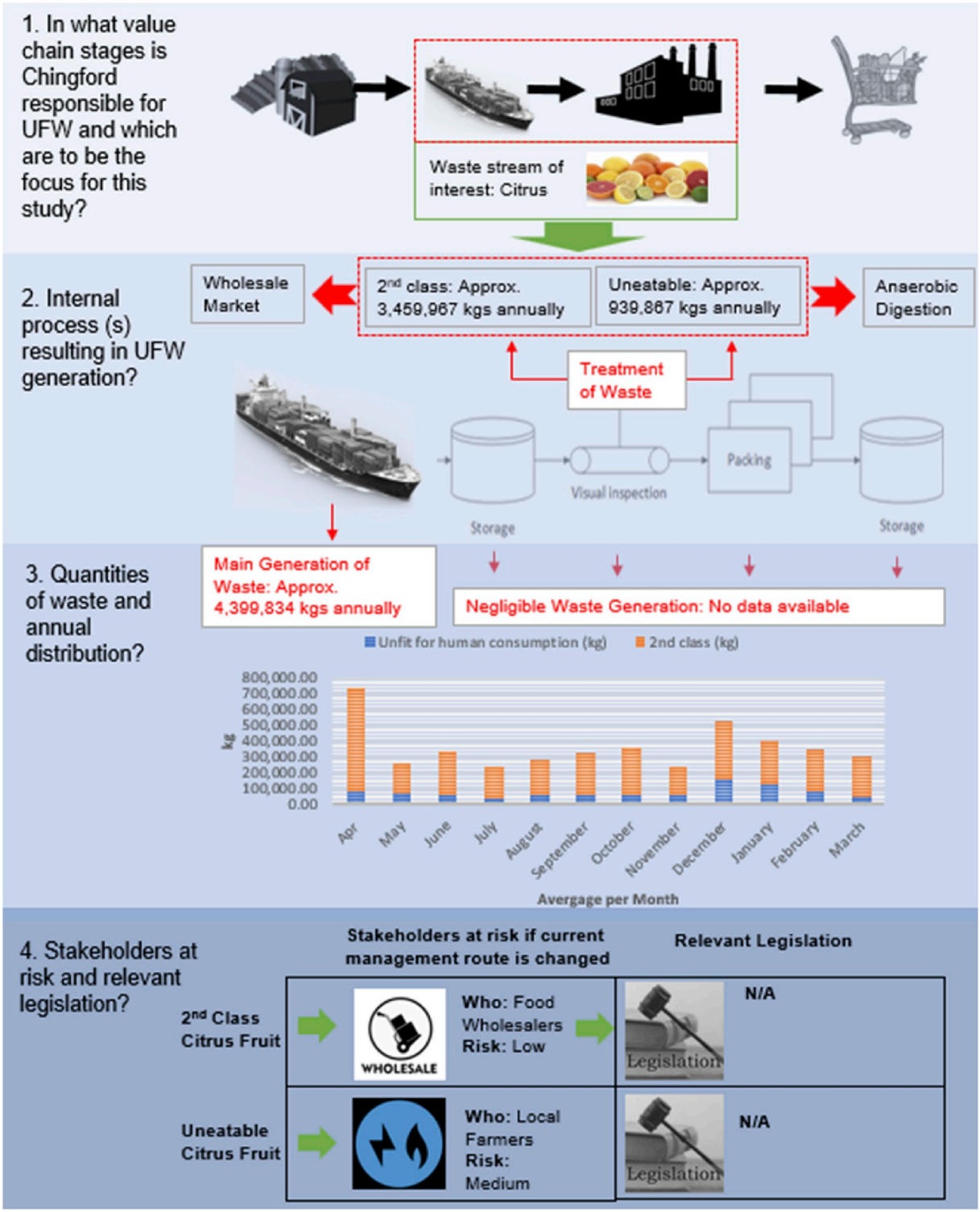


Fig. 3. Overview of conceptual modelling results for CF Fruits.

5.4. SWaVI stage 4: data collection and evaluation

Data for each of the selected evaluation criteria was collected in the evaluation matrix shown in Table 6. The values for each criterion correspond to valorisation of the total volume of 2nd class fruit produced by CF. Details on the collection, aggregation, weighting and normalization of each of the criteria presented in Table 6 can be found in the supplementary document. Findings suggest that economically, sale of 2nd class fruit to wholesale market, whilst resulting in significantly less value than if the fruit had been in 1st class condition, did result in a positive NPV because there were no additional costs associated with managing the waste in this way.

With regard to pectin extraction, even though pectin itself is more valuable per kg than 2nd class fruit, its extraction resulted in negative NPV because the yield of pectin is still relatively low compared to the volume of 2nd class fruit available for sale and requires significant capital investment and expenditure on running costs. In terms of environmental impacts, both scenarios demonstrated similar impacts

Table 6
Completed evaluation matrix for wholesale and MAPE scenarios.

Evaluation Criteria	Sub-Criteria	Unit	Pectin Extraction Valorisation Scenario	Wholesale Valorisation Scenario
Economic	Net Present Value	£	−26156509.91	23912776.27
Environmental	Climate Change Potential	kg CO_2-eq	190298185	7237.5
	Human Toxicity Potential	CTUh	41.19	0
	Photochemical Ozone Formation Potential	kg NMVOC eq	611260.84	20.7
	Acidification Potential	molecular H+ eq	964177.47	23.4
	Freshwater Eutrophication Potential	kg P eq.	65162.71	0.56
	Ozone Depletion Potential (ODP)	kg CFC-11-eq	6.04	0
	Ecotoxicity Potential	CTUe	1119875985.67	43500
Social	Social Acceptability	+/++	++	++
	Odor Generation	+/++	++	++
	Noise Creation	dB within 15 m	90	75
	Job Creation	Total jobs created	4	0
	Traffic	No. of vehicles	6.5	131
Technological Maturity	Technology Readiness	TRL Scale (1–9)	4	9
	Integration Readiness	IRL Scale (1–7)	6	7
	Demand Readiness	DRL Scale (1–7)	9	9
Alignment with Company Goals	Strategy Fit	Likert Scale (1–5)	4	2
	Brand Fit	Likert Scale (1–5)	4	3
	Expertise Fit	Likert Scale (1–5)	2	5

related to transport to consumers and whilst compared to conventional pectin extraction procedures, the MAPE process is more environmentally friendly, this is still an impact not borne by wholesale of 2nd class fruit.

The MAPE process for valorisation of citrus waste performed better from a social perspective due to its slightly higher job creation rate, lower noise generation and reduced transport impact due to pectin being produced in relatively lower volumes compared to 2nd class fruit. Social acceptability and odor generation were identified as being equal for both valorisation approaches. In terms of technological maturity, both scenarios scored highly in terms of demand readiness, reflecting growing global demand for pectin and an established market for 2nd class citrus fruit. However, as the MAPE process is relatively new and to the authors knowledge, only exists as a laboratory prototype, it scored lower for technological readiness and ability to integrate with other processes on site compared with the technologically simple and already proven method of storing 2nd class fruit for wholesale. With regard to alignment with company goals, clearly CF already has the established contacts to facilitate wholesale of citrus 2nd class waste, whereas they do not currently perform pectin extraction and would need to develop new expertise in this area, hence the higher score for wholesale. However, in terms of strategic fit, wholesale returns a low value and is susceptible to market prices. Therefore, in a season of glut, wholesale value may be very low whereas pectin could offer more stable and higher value as it is less prone to such fluctuations. Furthermore, in terms of brand fit, CF gains no advantage from anonymously providing fruit to the wholesale market, but if they were to produce jams using pectin, this could potentially enhance brand image. Hence the pectin extraction scenario scores highly in both strategic fit and brand image. An equal weighting was applied, and normalization performed to arrive at the final values for each valorisation scenario presented in Fig. 4. In this way, a higher score indicates better relative performance in an area

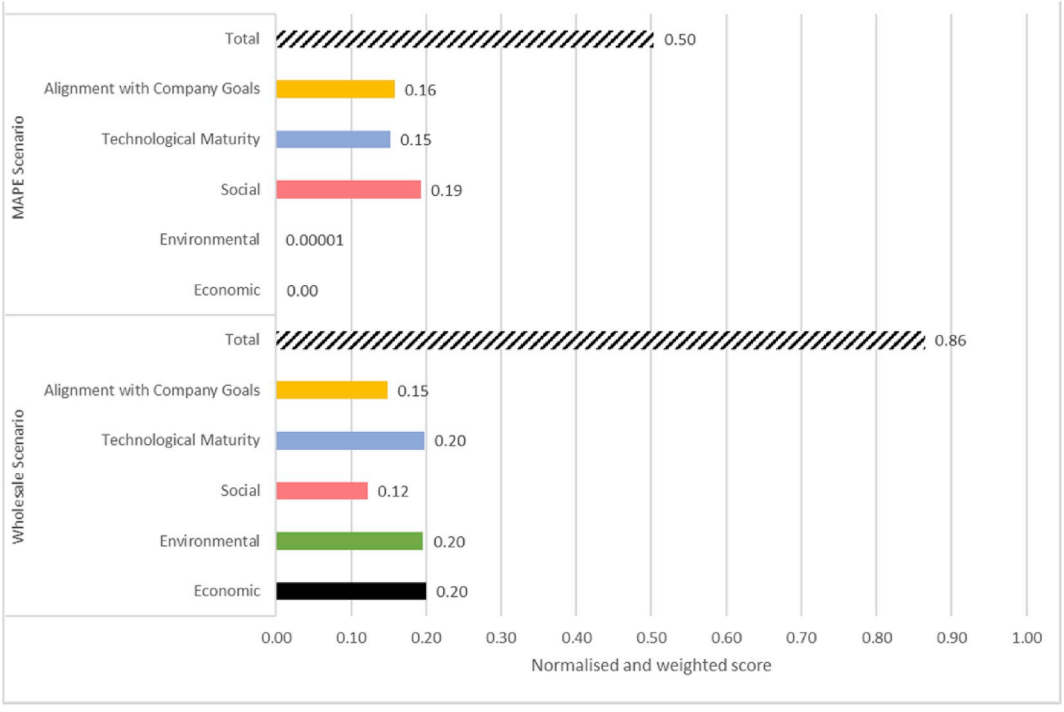


Fig. 4. Normalized, weighted and summed results for the pectin and wholesale waste valorisation scenarios.

compared to the alternative scenario and it can be seen that continued management of 2nd class fruit via wholesale remains the most viable method overall, predominantly due to its higher economic and environmental performance.

5.5. SWaVI stage 5: sensitivity analysis, interpretation and selection of valorisation strategy

A full sensitivity analysis was performed for all of the set-up and running costs modelled for each scenario. For the MAPE scenario, whilst energy intensity is a significant cost, it was identified that pectin was the most sensitive component and that an 80% increase in price could push this scenario into economic viability. This is important for CF to be aware of for future planning as a number of sources suggest that the global demand for pectin is likely to increase in coming years, with supply constraints pushing up its value further (Ciriminna et al., 2016). For the wholesale scenario, the most sensitive aspect was the value offered on the wholesale market for 2nd class citrus fruit, something that can vary hugely with global supply and demand. This being said, even if prices dropped on average by 50%, wholesale would still be the most viable solution for CF.

6. Concluding remarks

The SWaVI framework was designed to improve unavoidable food waste management in the food and drink manufacturing sector by enabling companies to identify potential valorisation strategies and select the one offering the best economic, environmental and social performance as well as technological maturity and alignment with company goals. It was developed from a thorough review of existing food waste valorisation assessment methodologies in the literature and demonstrated via a case study with a major UK based fruit consolidator, Chingford Fruits. In this case study the current method of managing 2nd class unavoidable citrus waste via wholesale was compared with a novel process to extract high-value pectin.

The results highlight that overall, wholesale currently is the optimal valorisation strategy, offering superior economic returns, environmental performance and technology readiness level. However, Microwave Assisted Pectin Extraction did offer improved social performance based upon job creation and noise levels as well as a better fit with company strategy and image as it is ultimately a way of upgrading rather than disposing of an otherwise unavoidable waste. Furthermore, sensitivity analysis suggests that in time, growing demand for pectin could push its value high enough to make the MAPE process viable. A key strength of the SWaVI framework is that its reliance on a combination of LCA, CBA and the weighted summation variant of MCDA enables it to quickly compare multiple valorisation options across a wide range of parameters using empirical rather than subjective inputs, thus giving it an advantage over other comparable tools (WRAP, 2019). Being based upon the relatively simple weighted summation approach, the SWaVI framework is also intended to be easy to apply and visually interpret, requiring minimal specialist knowledge and time commitments.

However, the framework is not without its limitation and the large amount of freedom provided to users to select indicators for use and weightings assigned mean that the outcome scores may not accurately represent the situation in reality. To overcome this, the framework presents strict evaluation criteria selection and weighting rules. It should also be stressed that it is not intended as a replacement for other life cycle-based modelling approaches such as LCA and LCC, rather, it is intended as a more streamlined method of initially selecting what is likely to be the best fit valorisation method and LCA, LCC are recommended to guide actual implementation. With regard to future work, there is a need for expanded empirical validation of the SWaVI framework in different food and drink manufacturing sectors to fully test whether the current evaluation criteria can adequality manage the full range of unavoidable food wastes generated across the food and drink manufacturing sector. Moving beyond this, the framework shows potential to be developed into a digital tool to which companies can input the relevant data and receive automated guidance on what are likely to be the best valorisation scenarios for their bespoke unavoidable food waste situation.

Conflicts of interest

The authors declare no conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2019.06.037.

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