Supplementary Material

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

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This supplementary article is intended to provide additional data that will aid readers in understanding the findings of the paper. Supplementary information specifically concerns Section 2, the review methodology, and section 5, the case study demonstration of the SWaVI Framework. This document now presents supplementary data from each of these sections respectively.

**1. Supplementary Data Regarding Section 2: Review Methodology**

Section 2 describes a thorough review of the literature describing how others have applied various research methodologies to aid in the selection/evaluation of food waste valorisation techniques. The final review list of 43 papers was not included in the main paper for space related reasons but is provided below in Table 1.

Table 1: Final pool of 43 papers identified in the review.

|  |  |  |  |
| --- | --- | --- | --- |
| Date | Author | Title | Journal |
| 2018 | Arora, A et al. | Process design and techno-economic analysis of an integrated mango processing waste biorefinery | Industrial Crops and Products. |
| 2018 | Iacovidou E, Ohandja DG, Voulvoulis N. | A multi-criteria sustainability assessment framework: development and application in comparing two food waste management options using a UK region as a case study. | Environmental Science and Pollution Research |
| 2018 | Demichelis F, Fiore S, Pleissner D, V.J. | Technical and economic assessment of food waste valorization through a biorefinery chain. | Renewable and Sustainable Energy Reviews |
| 2018 | Cristóbal J, Caldeira C, Corrado S, S.S. | Techno-economic and profitability analysis of food waste biorefineries at European level. | Bioresource technology |
| 2018 | Laso et al. | Combined application of Life Cycle Assessment and linear programming to evaluate food waste-to-food strategies: Seeking for answers in the nexus approach. | Waste Management |
| 2018 | Tesfaye T et al. | Valorisation of mango seed via extraction of starch: preliminary techno-economic analysis. | Clean Technologies and Environmental Policy |
| 2018 | Lam et al. | Life-cycle assessment on food waste valorisation to value-added products | Journal of Cleaner Production |
| 2018 | Brunklaus B, Rex E, Carlsson E, B.J. | The future of Swedish food waste: An environmental assessment of existing and prospective valorization techniques. | Journal of Cleaner Production |
| 2018 | De Menna F, Dietershagen J, Loubiere M, Vittuari M. | Life cycle costing of food waste: A review of methodological approaches | Waste Management |
| 2018 | Guerrero, A.B. and Muñoz, E. | Life cycle assessment of second generation ethanol derived from banana agricultural waste: Environmental impacts and energy balance | Journal of Cleaner Production |
| 2018 | Benis et al. | Putting rooftops to use–A Cost-Benefit Analysis of food production vs. energy generation under Mediterranean climates | Cities |
| 2018 | Cristóbal et al. | Prioritizing and optimizing sustainable measures for food waste prevention and management | Waste Management |
| 2018 | Schaubroeck et al. | A pragmatic framework to score and inform about the environmental sustainability and nutritional profile of canteen meals, a case study on a university canteen. | Journal of Cleaner Production |
| 2017 | Salemdeeb et al. | Environmental and health impacts of using food waste as animal feed: a comparative analysis of food waste management options. | Journal of Cleaner Production |
| 2017 | Lee et al. | Comparison and Evaluation of Large-Scale and On-Site Recycling Systems for Food Waste via Life Cycle Cost Analysis | Sustainability |
| 2017 | Diaz-Balteiro et al. | Measuring systems sustainability with multi-criteria methods: A critical review | European Journal of Operational Research |
| 2017 | Brancoli et al. | Life cycle assessment of supermarket food waste | Resources, Conservation and Recycling |
| 2017 | Rocha-Meneses L, Raud M, Orupõld K, Kikas T. | Second-generation bioethanol production: A review of strategies for waste valorisation | Agronomy Research |
| 2016 | Dimou C et al. | Techno-economic evaluation of wine lees refining for the production of value-added products. | Biochemical engineering journal |
| 2016 | San Martin D and Ramos S. | Valorisation of food waste to produce new raw materials for animal feed | Food chemistry |
| 2016 | Amienyo, D and Azapagic, A. | Life cycle environmental impacts and costs of beer production and consumption in the UK | The International Journal of Life Cycle Assessment |
| 2016 | Daylan B and Ciliz N. | Life cycle assessment and environmental life cycle costing analysis of lignocellulosic bioethanol as an alternative transportation fuel. | Renewable Energy |
| 2016 | Martinez-Sanchez et al. | Life-Cycle Costing of Food Waste Management in Denmark: Importance of Indirect Effects | Environmental Science & Technology |
| 2016 | De Menna F, Loubiere M, Dietershagen J, Vittuari M, | Methodology for evaluating LCC | REFRESH Deliverable 5 |
| 2016 | Christoforou E, Kylili A, Fokaides PA. | Technical and economical evaluation of olive mills solid waste pellets. | Renewable Energy |
| 2016 | Guinée J | Life cycle sustainability assessment: What is it and what are its challenges? | In Taking stock of industrial ecology 2016 (pp. 45-68). Springer |
| 2016 | Chong, Y and Teo, K. | A lifecycle-based sustainability indicator framework for waste-to-energy systems and a proposed metric of sustainability. | Renewable and Sustainable Energy |
| 2015 | Kwan et al. | Techno-economic analysis of a food waste valorization process via microalgae cultivation and co-production of plasticizer, lactic acid and animal feed from algal biomass and food waste | Bioresource technology |
| 2015 | Scherhaufer et al. | Criteria for and baseline assessment of environmental and socio-economic impacts of food waste | Fushions |
| 2014 | Vandermeersch T, Alvarenga RA, Ragaert P, D.J | Environmental sustainability assessment of food waste valorization options | Resources, Conservation and Recycling |
| 2014 | FAO | Food Wastage Footprint. Full-cost accounting. Final Report. | FAO |
| 2014 | Liu, J and Opdam, P. | Valuing ecosystem services in community-based landscape planning: introducing a wellbeing-based approach | Landscape Ecology |
| 2012 | Iacovidou, E and Ohandja, D. | Food waste co-digestion with sewage sludge–realising its potential in the UK. | Journal of environmental management |
| 2011 | Swarr et al. | Environmental life-cycle costing: a code of practice. | The International Journal of Life Cycle Assessment |
| 2011 | Kim et al. | Evaluation of food waste disposal options by LCC analysis from the perspective of global warming: Jungnang case, South Korea. | Waste Management |
| 2011 | Bernstad, A., La Cour Jansen, J | A life cycle approach to the management of household food waste—a Swedish full-scale case study. | Waste Management |
| 2010 | Jamasb, T. and Nepal, R. | Issues and options in waste management: a social cost–benefit analysis of waste-to-energy in the UK. | Resources, Conservation and Recycling |
| 2010 | Liu et al. | Valuing ecosystem services | Annals of the New York Academy of Sciences |
| 2007 | Den Boer J et al. | LCA-IWM: a decision support tool for sustainability assessment of waste management systems | Waste Management |
| 2007 | Kapepula KM et al. | A multiple criteria analysis for household solid waste management in the urban community of Dakar. | Waste Management |
| 2005 | Reich, M. | Economic assessment of municipal waste management systems—case studies using a combination of life cycle assessment (LCA) and life cycle costing (LCC. | Journal of Cleaner Production |
| 2005 | Lundie, S. | Life cycle assessment of food waste management options. | Journal of Cleaner Production |
| 2004 | Kijak, R and Moy, D. | A Decision Support Framework for Sustainable Waste Management. | Journal of Industrial Ecology |

**2. Supplementary Data Regarding Section 5: Case Study**

For reasons of conciseness, only information pertaining to the outcomes and implications of the case study demonstration of the SWaVI framework is presented in the main paper. Details on how data were collected, analysed and otherwise processed in order to arrive at the normalized weighted values for each indicator regarding the Microwave Assisted Pectin Extraction (MAPE) process and the sale of food waste via wholesale are described in detail here. This section begins with SWaVI Stage 1 and works through to SWaVI Stage 5. Data were collected from Chingford Fruit (CF) through site visits in spring 2017. In these visits, staff with an understanding of the creation and management of citrus waste at CF were interviewed, using a questionnaire for guidance, to identify sources, volumes and timings of waste, as well as linked value chain stakeholders and legislation. Data was collected for each month between April 2013 to March 2017. Once the initial data was collected and analysed, further communication with interviewees via email was established to collect missing data and clarify different aspects of the information already collected. Therefore, all information presented can be considered to have been provided by the industrial partners, unless another reference is given.

2.1 *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. All of the data collected relating to where in the supply chain CF had control over waste, the focus on citrus, and the division into ‘eatable’ and ‘uneatable’ classes with volumes and seasonality were obtained from the head of sustainability at Chingford's. Data pertaining to relevant policy was collected through the interview with CF’s sustainability manager and online investigation by the author. Finally, data regarding stakeholders, particularly Guy & Wright who currently use CFs uneatable waste for anaerobic digestion was collected through a site visit in spring 2017

2.2 *SWaVI Stage 2: Identification of Possible Valorisation Scenarios*

As outlined in the main article, currently, the fraction of citrus waste that is blemished but still edible (referred to as 2nd class waste) is sent to wholesale markets at a loss of approximately 80%. Fruit that is damaged or spoiled beyond the point that it can be safely consumed by humans is currently sent to anaerobic digestion at a local farm (uneatable waste). The goal of this stage of the case study was to find a valorisation process that could match the relatively high environmental and social performance of wholesale treatment but provide much better economic returns. It was identified, as described in the main article, that the extraction of high value compounds could achieve this better than alternatives, such as anaerobic digestion or animal feed and that pectin was perhaps the most valuable of the compounds that could be extracted (with global demand projected to rise significantly in coming years). Therefore, the chosen scenarios were sale of fruit to wholesale markets and a novel pectin extraction process known as Microwave Assisted Pectin Extraction. As CF does not currently perform MAPE, data required for the evaluation (associated with all of the evaluation criteria selected in Stage 5.3 of the main article) was empirically gathered in the laboratory at the University of York via site visits in Spring 2018. Conventionally, pectin extraction typically requires boiling in acidic conditions for several hours to release the pectin. However, by replacing this process with the use of microwaves, both the time requirements and the negative environmental impacts of the acid and high energy input to maintain boiling temperatures are reduced. Following this, the

resulting mixture can be filtered, and an organic alcohol applied to facilitate the precipitation of the pectin. The process, as performed by York is described by Garcia Garcia et al (2019) [1].

2.3 *SWaVI Stage 3:* *Selection of Evaluation Criteria*

Selection of evaluation criteria in this case study consisted of analysing the criteria displayed in Table 3 with interviewees from CF to identify which were most appropriate for CF, based on their relevance to production processes used, company strategy and supply chain position. Only Land Use Change (LUC) and Energy, Water and Mineral Efficiency (EWME) were excluded, the former because it was not affected by the actions of either of the two valorisation processes being compared and the later due to challenges in obtaining suitable data from CF.

2.4 *SWaVI Stage 4: Data Collection and Evaluation*

Values were recorded for each of the selected evaluation criteria in the evaluation matrix shown in Table 2 (corresponding to Table 6 in the main article). For each of the values shown in Table 2, a number of aggregation steps were often necessary, and this section describes such steps in full. As described in the main article, 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.

Table 2: 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 CO2-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 |
| 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 |

In this way, impacts for MAPE concerned those related to the on-site pectin extraction process and transport to the consumer. Impacts related to the production of citrus fruit and transport to CF were not included as they would have been borne as part of CFs normal operations regardless of how the waste is valorised. Likewise, for the wholesale scenario, impacts related to the transport of fruit to consumers and the actual sale of the fruit were considered (i.e. financial and social value).

The units for each of the criteria are listed in Table 2 and for all indicators, the functional unit was the impact per 3,459,967 kg of citrus waste managed, which is the quantity of 2nd class citrus waste generated by CF in a year. Some of the indicators could be measured directly, for example, all economic costs and benefits, environmental impacts and some social impacts such as noise creation, job creation and traffic generation. However, for certain criteria, such as odor generation, social acceptability, technology readiness level and company fit, objective measurement per unit of waste valorised is likely infeasible. In such cases, sub-criteria scoring takes the form of a position on an appropriate scale for the entire valorisation process. For example, noise and odor are scored using ++ for the most positive and + for the least. Technology readiness levels are scored using established technological, integration and demand readiness levels respectively (see Hjorth and Brem 2016 [2]). Company fit indicators are assessed on a likert scale with 5 representing complete fit, 3 representing acceptable fit and 1 representing no fit. This section will now work through the process of calculating each of the evaluation criteria listed in Table 2, beginning with the economic criteria.

The Net Present Values (NPV) for both wholesale marketing and the MAPE scenario were based on a detailed Cost-Benefit Analysis (CBA) of set-up and running costs associated using methodology outlined by Snell (2011) [3]. The annual costs and profits were then discounted over a standard 20 year lifecycle, using a discount rate of 1.5% to reflect the Bank of England’s current long term interest rate as of September 2018 [4]. The costs and benefits used to calculate the NPV for each valorisation scenario are presented in Table 3. CF identified that for the current wholesale scenario, they were not liable for any additional set-up, running or end of life costs (beyond which were already performed as part of day-to-day activities) and so the reported NPV is purely based on profit received for the sale of 2nd class produce. This was calculated based upon the average of prices received in the financial year 2016-2017 which was 35p per kg of 2nd class waste.

For the MAPE scenario however, CF would be liable for a range of equipment costs in year 1 and substantial running cost in subsequent years. Returns on pectin generated from the MAPE process were based upon the current average global pectin value of $15 per kg [5]. Costs were calculated based upon information provided by researchers at the University of York and are based upon the costs they encountered in the setup of their prototype MAPE process. In both scenarios, it was difficult to identify exact end-of-life costs. For the wholesale scenario, it is likely this process would continue beyond the 20-year cycle and for the MAPE scenario, it was anticipated that it would likely also continue, albeit with maintenance/replacement costs that were not captured in this case study because of the prototype nature of the existing system.

Table 3: Costs and benefits analysed to generate the NPV for each scenario.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| MAPE Scenario | | | Wholesale Scenario | |
| Project Stage | Cost Sources | Benefit Sources | Cost Sources | Benefit Sources |
| Set-up (Year 0) | 1. Orange Juicer (£780)  2. Mill cost (£5,977.76)  3. Blender (£1,106)  4. Sieve (£240)  5. Chiller (£325)  6. Microwave (£18,500)  7. Freeze Dryer (£4,200))  8. Pump (£9,617)  9. Boiler (£50)  10. Centrifuge (£7470)  11. Staff Cost (£25,000) | N/A | N/A | N/A |
| Operational (Values are per year, repeated through years 1-20) | 1. Energy Costs (£2,667,288,56)  2. Water Costs (£184,531.57)  3. Consumables (filter cloths, flasks and ethanol) (£537,678.87)  4. Staff cost (£95,000) | Pectin Value (£1,965,261.26) | N/A | 2nd class fruit value (£1,210,988.45) |
| Project Total | £-28,938,783.00 | | £24,219,769.00 | |
| Net Present Value | £-26,156,509.90 | | £22,002,011.72 | |

With these considerations in mind, it is not surprising that the wholesale scenario has a much higher NPV than the MAPE scenario purely due to lack of costs, whereas currently, the MAPE costs exceed the benefit received from pectin sales, even over a 20-year period.

Environmental sub-criteria for each scenario were calculated using SimaPro 8.5.2 (PRé Sustainability). ecoinvent 3.4 database and “Allocation at the point of substitution” (APOS) materials and processes were used to build the inventory. As for the Cost-Benefit Analysis, the functional unit was defined as 3,459,967 kg of citrus waste managed, which is the quantity of 2nd class citrus waste generated by CF in a year. A burden-free approach was used to allocate all environmental impacts to products sold by CF and none to wastes that enter the waste management system. The systems boundaries were defined to consider all processes needed to manage 2nd class citrus waste, i.e. transportation and MAPE processes, including emissions and resource depletion associated with the materials and processes used in these processes, e.g. electricity and water. Management of the residues generated in the processes, e.g. wastewater, is included within the scope of the study. The International Reference Life Cycle Data System ILCD 2011 Midpoint+ V.1.10 impact assessment method was used to calculate environmental impact indicators.

It is important to note that human toxicity potential includes cancer and non-cancer inducing toxicity and that eutrophication potential and ecotoxicity are both from a freshwater perspective only. For the wholesale scenario, additional environmental impact (i.e. that which would not be incurred by CF as a result of normal day to day actions) was from transport to market. Therefore, the calculation of environmental criteria was based upon a Euro 6 class lorry (larger than 36 metric ton) with refrigerated trailer carrying an average of 4613.2893 kg, 15 times a week, 50 times a year to account for all 2nd class fruit. For the MAPE scenario, additional environmental impact was based upon electricity, water and ethanol consumption. Results show that, currently, wholesale of 2nd citrus waste has superior environmental performance, but this is largely because the main environmental impacts from wholesale relate only to transport, whilst the MAPE process by nature also involves some processing of the waste citrus, leading to the relatively larger impacts across all environmental sub-criteria.

The values for social, technology readiness level and company fit were provided by CF during the interview process and did not require any processing before arriving at the values presented in Table 2. The values in Table 2 were then assigned an equal weighting as shown in Table 4 before being normalized using Equation 1 for non-beneficial criteria (e.g. environmental pollution) and Equation 2 for beneficial criteria (job creation) to arrive at the final values shown in Figure 1 (corresponding to Figure 4 in the main article).

Equation 1.

Equation 2.

Table 4. Weighting of individual criterion

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Criteria | Weighting | Sub-Criteria | Weighting | Individual Weighting |
| Economic | 1/5 | Net Present Value | 1 | 20% |
| Environmental | 1/5 | Climate Change Potential | 1/7 | 2.85% |
| Photochemical Ozone Formation Potential | 1/7 | 2.85% |
| Human Toxicity Potential | 1/7 | 2.85% |
| Acidification Potential | 1/7 | 2.85% |
| Eutrophication Potential | 1/7 | 2.85% |
| Ozone Depletion Potential | 1/7 | 2.85% |
| Ecotoxicity Potential | 1/7 | 2.85% |
| Social | 1/5 | Social Acceptability | 1/5 | 4% |
| Odor Generation | 1/5 | 4% |
| Noise | 1/5 | 4% |
| Job Creation | 1/5 | 4% |
| Traffic | 1/5 | 4% |
| Technological Maturity | 1/5 | Technological Readiness Level | 1/3 | 6.66% |
| Integration Readiness Level | 1/3 | 6.66% |
| Demand Readiness Level | 1/3 | 6.66% |
| Alignment with Company Goals | 1/5 | Fit with brand image | 1/3 | 6.66% |
| Fit with company strategy | 1/3 | 6.66% |
| Fit with company expertise | 1/3 | 6.66% |

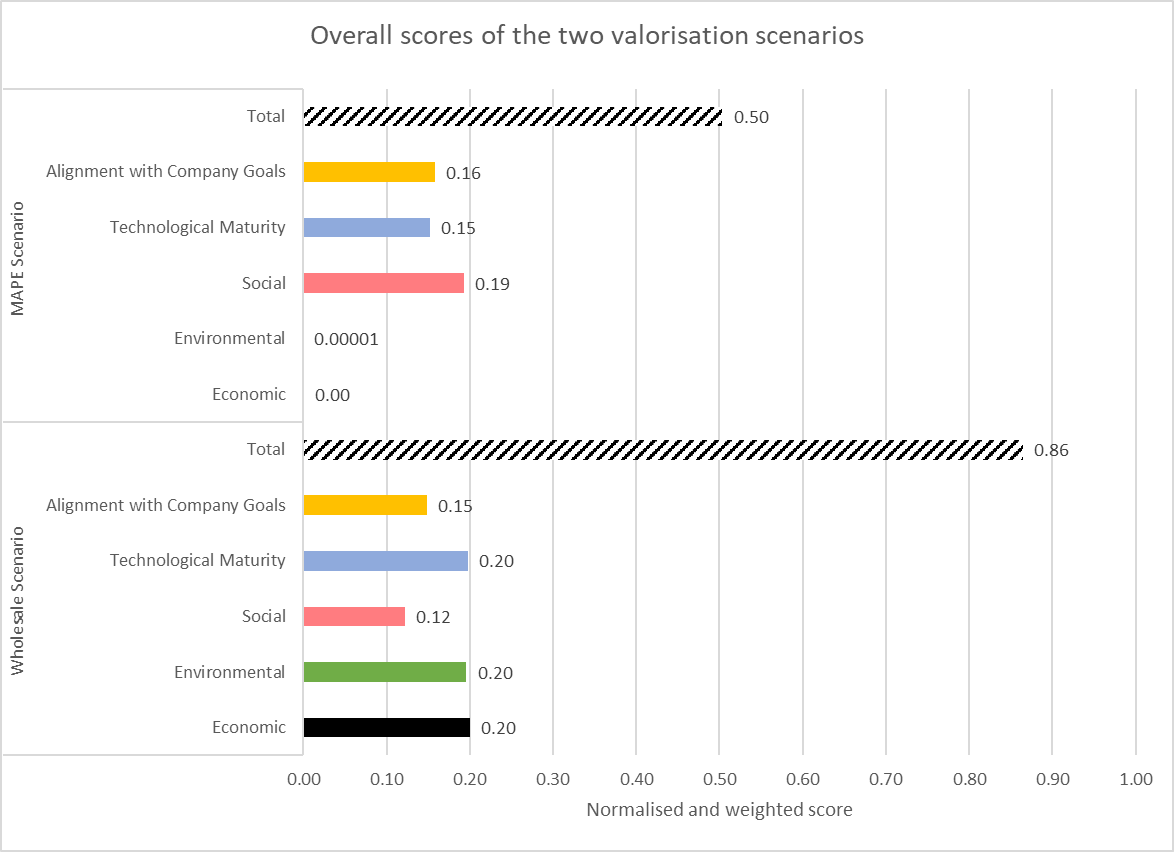
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Figure 1: Normalized, weighted and summed results for the pectin and wholesale waste valorisation scenarios.

2.5 *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. This was performed as a what-if analysis data table in Microsoft Excel where the costs for energy, consumable, labor costs and pectin value for the MAPE scenario and transport 2nd class citrus value for the wholesale scenario were increased and decreased incrementally by 5% to identify the point at which the scenario ceased to become viable.

**References**

1. Garcia Garcia G, Rahimifard S, Matharu AS, Dugmore TI. Life-Cycle Assessment of Microwave Assisted Pectin Extraction at Pilot-scale. ACS Sustainable Chemistry & Engineering.

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