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Life-cycle Assessment on Food Waste Valorisation to Value-added Products

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Abstract

Food waste can serve as a potential substitute for fossil-derived feedstocks for producing value-added chemicals, such as hydroxymethylfurfural (HMF), yet their environmental performance has not yet been evaluated, thus impeding informed decision-making. This study aims to develop a life-cycle assessment (LCA) framework to guide decisions on selecting the most environmentally favourable food waste valorisation option to produce HMF. A LCA framework was developed to assess the environmental performance of eight food waste valorisation scenarios with different combinations of solvents, catalysts, and experimental conditions. The environmental impacts associated with the use of water solvent, organic co-solvents, metal catalysts, as well as the reaction temperature and time were estimated. Experimental data were analysed for building the life-cycle inventory. The conversion of bread waste using water-acetone medium with the catalyst aluminium chloride ($AlCl_3$), at 140ºC for 30 minutes, was revealed to be the most environmentally favourable food waste valorisation option, due to the utilization of less polluting co-solvent (acetone) and catalyst (aluminium chloride) as well as the relatively high yield of HMF (27.9 Cmol%). It is expected that when the development of large-scale valorisation systems become more mature and information is more readily available, the decision-supporting tool could be expanded to (1) evaluate the pilot-scale and the industrial-scale of food waste valorisation to HMF, and (2) include the economic performance of the scenarios so that more comprehensive results could be provided to assist decision-making.

Keywords: Life-cycle assessment; biomass valorisation; waste recycling; biorefinery; hydroxymethylfurfural; catalytic conversion.

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1. Introduction

The continuous increase of global demand for energy and petroleum-derived chemicals has been exerting pressure on global climate change as well as the world's fossil resources reserves. This increase is mostly driven by the thriving economies such as China and India, which are estimated to have a total of 51% growth in energy demand in the year 2015-40 (van Putten et al. 2013; USEIA 2017). The depleting fossil reserves have aroused much attention, since petrochemicals have been vital for the production of various important chemicals and products such as polymers, solvents, pesticides, pharmaceuticals, and asphalt (Rout et al. 2016; Sheldon, 2016; Matsakas et al. 2017). Renewable biomass appears to be an ideal and sustainable substitute for fossils as it is a great carbon source with high contents of carbohydrates, lignocellulose, and fatty acids (van Putten et al. 2013). The need for biochemical production has been reflected by its remarkable global market value of $1 trillion USD, which could create 200,000 job opportunities in the US (Golden and Handfield 2014).

Previous studies have investigated conversion of biomass to biofuels and value-added chemicals via different biological technologies (e.g., fermentation) and chemical processes (e.g., pyrolysis and catalysis) (Schwartz et al. 2014; Karka et al. 2017). Carbohydrate-rich feedstock such as corn and sugarcane are widely used for ethanolfatty acid methyl ester can be generated from bread waste and waste cooking oils (Xiong et al., 2017; Yu and Tsang, 2017).

The valorisation of biomass to hydroxymethylfurfural (HMF) has been extensively studied as it is a versatile platform chemical, which has been listed as one of the top 10 bio-based chemicals by the US Department of Energy (Rout et al. 2016; Chen et al., 2017; Yu and Tsang, 2017). Derivatives of HMF are the building blocks of various products including pharmaceuticals, polymers, antifungal substances, and ligands (van Putten et al. 2013; Sheldon 2016). At present, commercial HMF production is primarily produced from sugarcane syrup (Kläusli 2014). The process of growing the energy crops, however, is suggested to pose threats to the environment because of soil and water contamination by pesticides and fertilisers (Karka et al. 2017). As a result, the call for a more sustainable way to synthesise HMF is imperative. A vast variety of valorisation methods with different substrates, catalysts, and solvents are demonstrated in the literature (Table 1). However, these studies focused on technological advancements for high-yield production of HMF without assessing the environmental impacts induced in the production process, which possibly hinders decision makers from evaluating the novel options in a holistic perspective. Thus, to identify and evaluate the environmental impacts of the HMF production process from waste biomass, a decision-supporting tool is required.

A number of studies evaluated the environmental feasibility of different biomass waste conversions via life cycle assessment (LCA). For instance, Woon et al. (2016) studied the environmental impacts of using food waste to generate biogas through anaerobic digestion, while another study carried out by Vandermeersch et al. (2014) also considered the possibility of producing heat and energy through food waste (Scenario 1), with another scenario of animal feed production (Scenario 2) for comparison. Karka et al. (2017) conducted a large-scale LCA of the production of 23 products including various chemicals, biodiesel, and biogas using five different types of biomass waste (wood chips, municipal solid waste, rapeseed oil, wheat straw, and waste cooking oil). The majority of these LCA studies targeted the environmental impacts on biogas or energy production, with only a few on high value-added chemicals. To the best of our knowledge, LCA on biomass waste valorisation to HMF has not been conducted. Thus, this paper intends to fill this research gap by entirely focusing on the production process of this high-valued chemical.

In this study, food waste is chosen as a representative of waste biomass for evaluation because food waste accounts for nearly one-third of municipal solid wastes (MSW) in Hong Kong (HK EPD 2016) and other densely populated cities. Globally, one-third of the total food production that amounts to approximately 1.3 billion tons is being disposed per year, generating 3.3 billion tons of CO_2 equivalent and causing an annual economic loss of \$750 billion USD (Gustavsson et al., 2011; FAO, 2013). Catalytic conversion approaches have been recently developed to produce HMF from food waste (Yu et al., 2016; Yu et al., 2017a). Yet, their environmental performances have not yet been evaluated. Trade-off between the technological performance and environmental compatibility often renders decision making difficult. For instance, using water as the reaction medium is environmentally benign, but the resultant HMF yield is usually inferior to that in organic solvent-containing medium (Yu and Tsang, 2017).

Therefore, the primary aim of this study is to develop an LCA framework to assess the environmental significance of various system components (solvents, catalysts, reaction temperature, reaction time, etc.) in the food waste-to-HMF process, by comparing the environmental impacts arising from eight laboratory-scale conversion systems as the pilot scheme is yet to be established. This study could assist researchers in designing green catalytic systems for biomass waste valorisation, as well as advise decision makers in sustainable management of biomass waste in long term.

2. Methodology

LCA is known as a ‘cradle to grave’ approach for evaluating the entire life-cycle environmental impacts of a process, service, or product (Nanda et al. 2015). The associated energy and resource consumption, together with the emissions for the whole system are being assessed (Gonzalez-Garcia et al. 2017). To systemically carry out a LCA, four steps have to be followed according to ISO 14040 standard (ISO 14040 2006; Parajuli et al. 2017), which are 1) goal and scope definition: defining the objective, system boundary, and the functional unit; 2) data collection and inventory analysis: explaining and presenting the life-cycle inventory data for the assessment; 3) Life cycle impact assessment: selecting the impact categories for the energy and resource, as well as the emission generated, and; 4) Results interpretation and presentation: reporting the results as detailed as possible with the suggestions on impact reduction.

2.1 Goal and scope definition

The goal of this LCA is to assess and compare the environmental performance of eight experimental methods for producing HMF from food waste, which significantly differ in terms of the operating parameters (i.e., process inputs) and product yields (i.e., process outputs). The LCA is conducted in this study to evaluate the environmental burdens and benefits originated from the raw material acquisition, material processing, production and the yield of final products. The functional unit (FU) is defined as the conversion of 1 g of food waste substrates.

The scope of this LCA covers eight scenarios of catalytic conversion of food waste to HMF, including processes of the use of solvent and co-solvents, the addition of catalysts, heating, and yielding of HMF. Water was used as the solvent in all scenarios, while various organic solvents were used as the co-solvents. Either tin (IV) chloride ($SnCl_4$) or aluminum chloride ($AlCl_3$) were used as the catalysts. Microwave reactor was used for the heating process. The environmental consequences related to such processes were included in the system boundary, which determines what processes and activities are included in the LCA (Figure 1).

2.1.1 Descriptions of LCA scenarios

Scenario 1 (S1) used bread waste as the substrate of the conversion process. $SnCl_4$ was used as the catalyst and added to the organic solvent-water medium, which was prepared using water and dimethyl sulfoxide (DMSO). The mixture was heated to 160ºC with a reaction time of 20 minutes.

Scenario 2 (S2) used the same substrate, organic solvent-water medium, catalyst and reaction time as S1. The reaction temperature was 140ºC in S2.

Scenario 3 (S3) was the conversion of bread waste substrate to HMF using DMSO-water medium and $SnCl_4$ catalyst. The reaction temperature and time were 140ºC and 60 minutes respectively.

Scenario 4 (S4) was the conversion of bread waste substrate to HMF using a medium of water and tetrahydrofuran (THF), and $SnCl_4$ as the catalyst. The mixture was heated to 140ºC and the reaction time was 120 minutes.

Scenario 5 (S5) used an acetone-water medium with the addition of $SnCl_4$ catalyst for the conversion of bread waste to HMF. The reaction temperature and time were 140ºC and 10 minutes respectively.

Scenario 6 (S6) converted bread waste substrate to HMF using an acetone-water medium and $AlCl_3$ as the catalyst. The mixture was heated to 140ºC and allowed for reaction for 30 minutes.

Scenario 7 (S7) used rice as the food waste substrate. A DMSO-water medium was used, and $SnCl_4$ was used as the catalyst. The reaction temperature and time were 140ºC and 40 minutes respectively.

Scenario 8 (S8) used kiwi fruit as the food waste substrate. The $SnCl_4$ catalyst was added to the DMSO-water medium. The mixture was heated to 140ºC and allowed for reaction for 20 minutes.

2.1.2 Descriptions of food waste conversion experiments

Food waste and chemicals

Food waste produced from the Hong Kong International Airport, including bread, rice and kiwifruit wastes, were collected for the experiments. The samples were freeze-dried, ground, and sieved through a 0.2 mm mesh for storage in an airtight storage container at 4^{o}C before use. Drying is only employed for experimental investigations and is not needed in the scaled-up application, where the indigenous water content of food waste will be used as a water solvent. Co-solvents including dimethyl sulfoxide (DMSO; ≥99.9%) and tetrahydrofuran (THF; ≥99.8%) from RCI Labscan, and acetone (99.5%) from Duksan Pure Chemicals were used to prepare the reaction medium. The metal chloride catalysts, $SnCl_4 \cdot 5H_2O$ (98%) and $AlCl_3 \cdot 6H_2O$ (ACS grade), were purchased from Sigma Aldrich and Anaqua, respectively. All the chemicals were used as received.

Process of Catalytic conversion

The process of catalytic conversion of food waste was reported in our previous studies (Yu et al., 2016; Yu et al., 2017a, 2017b, 2017c). In brief, 1 g of dried food waste as the substrate (equivalent to the concentration of 5 wt/v%), 10 ml of organic solvent and 10 ml of water as the reaction medium, and 0.39 or 0.27 g of metal chloride catalyst ($SnCl_4$ or $AlCl_3$, equivalent to the concentration of 55.5 mM) were mixed. The mixture was heated to 140-160^{o}C in an Ethos Up Microwave Reactor (Milestone, maximum power 1900 W), with the reaction time held between 10-120 min under magnetic stirring. The inputs of the process include food waste, organic solvent, water, metal chloride, and microwave energy (flow quantity shown in Table 2). Diluted and filtered samples were analysed by high-performance liquid chromatography (HPLC) to reveal the HMF yield, i.e., the process output, resulted from each scenario, using the Chromaster (Hitachi) equipped with an Aminex HPX-87H column (Bio-rad). All the trials were conducted in duplicate.

2.2 Life-cycle inventory analysis

Life-cycle inventory (LCI) analysis is the phase of accounting the inputs and outputs of materials and energy of the system being studied. The full account of inputs and outputs provides the fundamental information for further estimation of environmental impacts in the next phases. In this study, the details of the conditions of the laboratory conversion process of food waste to HMF were organized and used to build the LCI (Table 2). The electricity consumption for heating the reaction mixture was calculated based on the power of the microwave reactor and the duration of heating using the equation $E = P \times t$ (E denotes energy, P denotes power and t denotes time). The amounts of solvent, co-solvents, catalysts, and HMF were measured from the experiments.

2.3 Life-cycle impact assessment

Based on LCI analysis of the inputs and outputs of the systems, the induced environmental consequences were estimated in the life-cycle impact assessment (LCIA) phase. The ReCipe Endpoint method was adopted for conducting the LCIA. Instead of the individualist (short-term and optimistic) or the egalitarian (long-term and precautionary) models, this study adopted the hierarchist model (PRé Sustainability; Huijbregts et al. 2016), which has been recognized as the consensus model. The hierarchist model was selected as the temporal boundary and the mechanisms of the impacts used in such model are based on scientifically credible data (PRé Sustainability; Huijbregts et al. 2016). Eighteen midpoint indicators and three endpoint indicators are analysed in the ReCipe Endpoint method. The software SimaPro 8.3.0.0, which is a widely recognized LCA tool, was used in this study.

The solvents and electricity were produced through relatively common processes, thus the information on the associated environmental emissions is available in databases. Such information was adopted from the EcoInvent database in this study. To fit the local situation, emissions associated with electricity consumption were estimated by considering the fuel mix for electricity generation in Hong Kong: 53% coal, 22% natural gas, 23% nuclear and 2% renewable energy (HK ENB 2014).

The environmental emissions originated from the production process of $SnCl_4$ and $AlCl_3$ have not yet been documented in the databases, thus such emissions were estimated according to the method used by the EcoInvent for building life-cycle inventories of chemicals in order to ensure the consistency (Althaus et al., 2007). The reactions of metals with chlorine gas at elevated temperature were assumed to be the synthesis method to produce the metal chlorides, as represented by Equation 1 for $SnCl_4$ and Equation 2 for $AlCl_3$.

$$Sn + 2\,Cl_2 \xrightarrow{115°C} SnCl_4 \text{ ------ Eq. (1)}$$

$$2\,Al + 3\,Cl_2 \xrightarrow{650-750°C} AlCl_3 \text{ ------Eq. (2)}$$

Stoichiometric calculations were used to estimate the quantity of elemental metals and chlorine gas required. The energy for elevating the reaction temperature was also included in the analysis.

The conventional approach to produce HMF was neither documented in the previous LCA studies nor the databases. In this study, the reaction between sugar syrup (fructose) and sulfuric acid at a temperature of 166ºC was assumed (Fachri et al. 2015). Based on such study, 2.55 g of sugar syrup, 0.07 g of sulfuric acid and 0.21 kWh of electricity are required for producing 1 g of HMF (Fachri et al. 2015). The environmental impacts of sugar production and sulfuric acid were obtained from the Agri-footprint (Blonk Consultants 2015a, b) and the U.S. LCI (Franklin Associates 2011) databases, respectively. The Hong Kong fuel mix for electricity generation was considered during the estimation of impacts associated with electricity consumption. The avoidance of starting materials (sugar syrup and sulfuric acid) usage and energy consumption for heating via food waste valorisation were considered in the evaluation of environmental performance.

The LCIA includes the steps of classification, characterization, normalization, weighting and aggregation. The environmental emissions were classified into different categories according to the eighteen midpoint indicators, and then characterized into common equivalent units which reflects their contributions to the midpoint impacts. The characterized impacts were then normalized against the world average impacts, so that the relative importance of the impacts in different categories could be considered in the LCA. The normalized results were weighted and aggregated to provide single score LCA results, which are inclusive and convenient indicators to guide decision-making.

3. Results and discussion

The overall LCA results showed that S6 performed the best among the eight scenarios, while S4 was the least environmentally favourable option. To understand the details on the environmental implications, the results of different LCIA phases, namely characterisation, normalisation, and weighting and aggregation, were analysed and discussed in the following sections. The single-score results were further segregated according to the contributions of different processes.

3.1 Characterisation results

The environmental impacts of the scenarios in different impact categories are presented in Figure 2. In each impact category, scenarios with the highest impact were assigned the value 1, while other scenarios with lower impact were assigned the values between 0 and 1 by referring to the highest impact. Negative values refer to the environmental benefits achieved. The scenarios with relatively lower impacts, i.e., points plotted closer to the centre of the graph, have better environmental performance.

Among the scenarios, S4 performed the most unfavourably in all impact categories, which was possibly attributed to the use of THF as the co-solvent and the corresponding less favourable HMF yield compared to majority of the studied systems (Table 2). In comparison, S6 generated apparently lower impacts in natural land transformation (NLT) and metal depletion (MD) compared with the other scenarios because S6 was the only scenario that used $AlCl_3$ instead of $SnCl_4$ as the catalyst. The production of $AlCl_3$ requires the utilization of aluminium mines, while $SnCl_4$ production requires the mining of tin ores. The major reason for the difference was the abundance of metal resources: aluminium is one of the most abundant metals, but tin is a relatively limited natural resource (Smith and Huyck, 1999). The utilisation of aluminium, therefore, causes much lower environmental stress in terms of NLT and MD impacts than that of tin.

The yield of HMF from food waste avoided the environmental impacts of the industrial HMF production process from sugar syrup, thus offering notable environmental benefits. When the environmental savings could compensate for the negative impacts, net environmental benefits could be accomplished, as demonstrated by the negative values in marine eutrophication (ME) categories achieved by S1, S5, S6, S7, and S8 (Figure 2).

3.2 Normalization results

Most scenarios except S6 showed the highest impact in the MD impact category (Figure 3). The major reason is the high environmental stress associated with the use of the limited resource of tin metal for catalyst production in most of the studied scenarios, underscoring that catalyst selection was critical for sustainable management of metal resources. Following the MD impact, marine ecotoxicity (MX), freshwater ecotoxicity (FX), and human toxicity (HT) emerged as the significant impacts. The most significant contributors to such impact categories were the production of co-solvents, including THF, DMSO, and acetone, which are listed in descending order of toxicity impacts and consistent with the findings of Capello et al. (2007). The storage of THF produces organic peroxides (Guan and Guan 2012), which are toxic chemicals that could cause human fatality through inhalation, ingestion and dermal contacts (Faggian and Faggian 2014; Government of Canada 2017). The inhalation of THF has been identified to be carcinogenic in laboratory tests on rodents (Faggian and Faggian 2014). Previous studies have revealed that the lethal dosages of DMSO exposure in tests on rodents and fish were much higher than those of THF, indicating that DMSO has lower level of toxicity on human and aquatic ecosystems (Faggian and Faggian 2014). Both DMSO and acetone have been recognised as environmentally friendly solvents with low toxic potential to human (Soroko et al. 2011). Yet, DMSO exposure has been observed to induce higher levels of stress proteins (indicators for toxic response) than acetone exposure in fish embryos, implying that DMSO has higher aquatic ecotoxicity than acetone (Hallare et al. 2006). Production of co-solvents was also identified to be the major contributor to the freshwater eutrophication (FE) impacts. The impacts on fossil depletion (FD), particulate matter formation (PMF), terrestrial acidification (TA), climate change (CC) and photochemical oxidant formation (POF) were attributed to the energy consumption.

3.3 Single score LCA results

The above characterisation and normalisation results revealed the environmental performance of the scenarios in different mid-point categories, yet single and all-inclusive indicators to guide decision-making were not provided. Thus, the normalized results were assigned weightings and aggregated using the ReCipe Endpoint methodology so that single score results could be obtained. The single score LCA results of the eight scenarios of food waste valorisation are shown in Figure 4. The environmental impacts are presented in milli-points (mPt), which reveal the overall impacts of the scenarios. The results indicate that S6 is the most environmentally friendly option, while S4 is the most polluting scenario.

The environmental impacts were categorised into the Human health, Ecosystems and Resources aspects. The impacts in Resources aspect were the highest, contributing to 74% to the overall impacts on average (Figure 4). The high environmental stress on resources depletion is mainly attributed to the use of the relatively limited tin resources for producing the metal chloride catalyst. Human health impacts ranked after impacts on Resources with an average contribution of 25% to the overall impacts. The production of organic solvents, especially THF, and the metal mining process caused adverse impacts to human health. As mentioned above (Section 3.2), exposure to organic solvents through different routes has been revealed to cause human health threats, such as cancer and fatality. The excavation activity of tin mining and the disposal of tailings change the radionuclide compositions in soil, thus increasing the chance of radiological exposure of mine workers and nearby residents (Arogunjo et al. 2009; Aliyu et al. 2015). During bauxite mining for $AlCl_3$ catalyst production, the excavation activities release air pollutants, such as dust and fine particulate matters, that harm the respiratory and cardiovascular systems after inhalation (Abdullah et al. 2016). Drinking water could also be polluted by the discharge of bauxite washing water. Chronic ingestion of metal-containing water may increase cancer risks. The environmental emissions from energy consumption and the production processes of organic solvents and metal catalysts caused eutrophication, toxicity, and climate change impacts to the ecosystem. The scenarios in this study had relatively low impacts on the Ecosystems aspect (0.27% - 2.78% of the overall environmental impacts).

3.4 Single score LCA results with process contributions

To investigate the significance of different system parameters (i.e., reaction temperature, reaction time, solvents, etc.) in determining the total environmental impacts, the single score LCA results are presented to illustrate the individual process contributions (Figure 5). The processes involved in the conversion of food waste to HMF included the utilisation of solvent, co-solvents, catalysts, energy, and the yield of HMF. The use of solvents, catalysts, and energy contributed to the adverse environmental impacts, while the production of HMF recovers untapped value from food waste to synthesise high-value products and presents an alternative to petroleum refinery, thus providing environmental benefits that should be properly recognized and quantified. In all the scenarios, the use of water as solvent only contributed to trivial environmental impacts (only accounted for 0.003% of the overall impacts on average). The water use was assumed to obtain from conventional potable water treatment methods, which presented significantly lower environmental impacts compared to other processes, such as the production of organic solvents and metal chlorides. It should be noted that in industrial applications, water solvent should come from the indigenous water content of food waste where additional water demand can be avoided or minimised.

In the following sections, the environmental impacts of the scenarios are compared based on the choices of reaction temperature and reaction time, as well as the selection between various organic co-solvents and the two types of catalysts.

3.4.1 Energy input

The HMF production efficiency can be improved with higher energy input, which can be achieved by increasing the reaction temperature or lengthening the retention time. S1 and S2 are bread waste conversion to HMF in DMSO-water medium with the $SnCl_4$ as the catalyst. The reactions were allowed for 20 minutes. S1 used a higher temperature (160ºC) than S2 (140ºC), so that a higher yield of HMF could be obtained. The energy consumption for S1 was a double of that for S2, yet the HMF yield of S1 was only 70% higher than S2. The LCA results indicated that although S2 yielded less amount of HMF, the reduced energy consumption still provided it the environmental advantage over S1. S2 and S3 are scenarios with the same reaction conditions except the reaction time. With a threefold length of reaction time, S3 produced 0.199g HMF/g substrate, which was 58% higher than the yield in S2. However, the environmental benefits from HMF production could not compensate the extra energy consumption for the longer heating time, so S3 was less environmentally favourable than S2. These results highlighted that increasing the energy input (either reaction temperature or time) may not be a feasible approach for improving the HMF yield from the environmental perspective. Among all the scenarios, energy consumption-related impacts were the highest in S4 that involved THF as the co-solvent (Figure 5), which disfavoured catalytic conversion and, thus, resulted in a high energy demand for noticeable HMF production (Table 2). This suggested the indirect effects imposed by other system components on the magnitude of environmental impacts associated with energy inputs during the conversion process.

3.4.2 Organic co-solvents

Three types of organic co-solvents, including THF, DMSO and acetone, were used in the different scenarios. THF used in S4 was the co-solvent that contributed the most significantly to the environmental burden of the scenarios, while the use of DMSO (in S1, S2, S3, S7 and S8) and acetone (in S5 and S6) presented much lower environmental impacts than THF. The environmental impacts associated with the co-solvents were attributed to two major factors: the toxicity of the organic co-solvents and the energy requirement in the solvent production processes. The solvents with descending order of toxicity levels are THF > DMSO > acetone and the details were discussed in Section 3.2. The solvents with descending order of energy-associated impacts (including climate change, photochemical oxidant formation, acidification and fossil fuel depletion) are THF > acetone > DMSO. The production of THF has been revealed to be incurring the highest environmental impacts among the three solvents because the petrochemical production process involves numerous conversion steps with high energy and resource requirements (Capello et al., 2007). Methanol, the starting material for THF production, is oxidized to formaldehyde. The Reppe synthesis process used to convert formaldehyde to butylene glycol is energy-intensive, thus is one of the major contributors to the environmental impacts (Capello et al. 2009). Yet, the most dominant factors for the impacts were the cyclization and dehydration processes for the conversion from butylene glycol to THF, owing to the high energy and resource demand (Capello et al. 2009). Acetone could be produced from benzene in BTX (mixture of benzene, toluene and xylene). Benzene is alkylated to cumene, which is an intermediate chemical, and then converted to acetone through the Hock process (ACS 2017). Such production process incurred relatively low environmental impacts because of the low requirements for ancillary chemicals and energy (Capello et al. 2009). Using the same starting chemical as THF, the production of DMSO presented much lower energy-related impacts because DMSO could be simply produced by the oxidation of dimethyl sulphide, which is produced from reacting methanol with hydrogen sulphide (Capello et al. 2009; Bertau et al. 2014).

Accounting for the toxicity, energy-associated impacts and other relatively minor impacts, the overall environmental impacts per mass of solvents are THF > acetone > DMSO. However, scenarios using acetone (S5 and S6) in this study produced lower solvent-related impacts than those using DMSO (S1, S2, S3, S7 and S8), because the former scenarios required larger mass of co-solvents (acetone; 7.85g) than the latter ones (DMSO; 11.00g).

3.4.3 Catalysts

The catalyst $AlCl_3$ used in S6 showed trivial environmental impacts, while, in contrast, the $SnCl_4$ catalyst was the most or the second-most dominant polluter in other scenarios. One of the factors contributing to the difference was the different abundance levels of the metal resources:aluminium resource is abundant while tin is a relatively limited metal resource (Smith and Huyck, 1999). The preparation of elemental tin has also been identified to be more polluting than that of elemental aluminium. Elemental tin is refined from tin metal, which could be prepared from cassiterite mining and further processing. Elemental aluminium is prepared from primary and secondary aluminium metal. To obtain primary aluminium, bauxite is mined and concentrated into aluminium hydroxide, which is then purified to aluminium oxide. Primary aluminium could be yielded by refining aluminium oxide. Secondary aluminium metal, which is recovered from scrap, is another source of elemental aluminium. The LCA study on metals conducted by Nuss and Eckelman (2014) revealed that the preparation of elemental tin performed less environmentally favourable than that of elemental aluminium in global warming potential, cumulative energy demand, acidification, eutrophication and human toxicity. Such findings corroborated the higher environmental impacts from $SnCl_4$ production than that from $AlCl_3$ in this study.

3.4.4 HMF production

The conversion of food waste to HMF avoided the impacts of conventional HMF production process, which involved the inputs of crop-derived fructose syrup , acid catalyst, and energy supply (Fachri et al., 2015). The different yields of HMF obtained offered environmental benefits that compensated for 3.86% of the environmental burdens in the most polluting scenario and 36.86% of those in the most environmentally favourable scenario, respectively. The HMF yield could be increased by increasing the reaction temperature (S1 compared to S2), lengthening the reaction time (S3 compared to S2) and using acetone as the co-solvent (S5 and S6). However, in S1 and S3, the environmental benefits from higher HMF yield could not compensate for the increased energy consumption for heating. In S5, the use of $SnCl_4$ caused significant environmental drawbacks that overwhelmed the environmental benefits of the scenario. After balancing the damages and benefits, S4 was revealed to be the most environmentally favourable option.

4. Conclusions

To inform the decision-making on the selection of the best food waste valorisation option, this study developed an LCA framework for evaluating the environmental performance of the food waste valorisation scenarios by including the major processes of the utilization of solvent, co-solvents, catalysts, energy and the recovery of HMF. The LCA conducted in this study assessed eight scenarios of food waste valorisation via catalytic conversion, and concluded that S4 is the most polluting scenario while S6 is the most environmentally favourable option. The use of a less polluting catalyst ($AlCl_3$) and co-solvent (acetone), as well as the relatively high yield of HMF (27.9 Cmol%), provided S6 the superior environmental performance. Metal depletion impacts, which were attributed mainly to the production of metal chlorides catalyst, were the highest among the categories, followed by the toxicity impacts (marine ecotoxicity, freshwater toxicity, and human toxicity) which were contributed mostly by the production of organic co-solvents. The energy and $SnCl_4$ catalyst consumptions were the most dominant factors of the environmental impacts in most of the scenarios.

To keep the consistence of the framework while the detailed economic information about catalyst recycling was unavailable, only the environmental aspect was considered in this study. However, when the development of such valorisation process become more mature, and the information is more readily available in the future, the inclusion of the economic aspect is expected, so that a more comprehensive decision-supporting tool could be developed. The LCA in this study acts as an early milestone for guiding the selection of the best valorisation process, thus contributing to the development of the waste valorisation systems.

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Table 1 Valorisation of Lignocellulosic biomass to HMF

Biomass	**Solvent**	**Catalyst**	**Temp (°C)**	**Time**	**HMF yield (%)**	**References**
Corn stover	DMA-LiCl; [EMIM]Cl	$CrCl_2$; HCl	140	2 h	48	Binder & Raines, 2009
Corn stover	DMA-LiCl; [EMIM]Cl	$CrCl_2$	140	6 h	16	Binder & Raines, 2009
Cassava waste	Acetone; DMSO; Water	Sulfonated carbon-based catalyst	250	1 min	12.1	Daengprasert et al., 2011
Corn stalk	[BMIM][Cl]	corn stalk-derived carbonaceous solid acid catalyst	150	30 min	44.1	Yan et al., 2014
Raw corn stalk	GVL; Water	PTSA-POM	190	100 min	19.5	Xu et al., 2015
Corn stalk	GVL	SC-CCA	210	1 h	2.2	Zhang et al., 2016
Sugarcane bagasse	NMP	SPPTPA-1	140	1 h	19.8	Mondal et al., 2015
Sugarcane bagasse	DMA-LiCl	SPPTPA-1	140	20 min	5.7	Mondal et al., 2015
Sugarcane bagasse	DMSO	SPPTPA-1	140	1 h	18.8	Mondal et al., 2015
Rice straw	[BMIM][Cl]	$CrCl_3$	200	3 min	47	Zhang, 2010
Rice straw	[MIM]HSO_4	N/A	160	30 min	7.9	Yokohama & Miyafuji, 2016
Bread waste	ACN; Water	$SnCl_4$	140	10 min	26	Yu et al., 2017
Bread waste	Acetone; Water	$SnCl_4$	140	10 min	26	Yu et al., 2017
Bread waste	DMSO; Water	$SnCl_4$	140	1 h	27.4	Yu et al., 2017
Bread waste	THF; Water	$SnCl_4$	140	2 h	8	Yu et al., 2017

Table 2 LCI of food waste valorisation

	Process input					Process output
	Food waste (1 g)	Solvent (10 mL)	Co-solvent (10 mL)	Catalyst	Electricity (Wh)	HMF yield (g)
S1	Bread waste	Water	DMSO	$SnCl_4$; 0.289g	100.0	0.214
S2	Bread waste	Water	DMSO	$SnCl_4$; 0.289g	50.0	0.126
S3	Bread waste	Water	DMSO	$SnCl_4$; 0.289g	150.0	0.199
S4	Bread waste	Water	THF	$SnCl_4$; 0.289g	400.0	0.109
S5	Bread waste	Water	Acetone	$SnCl_4$; 0.289g	33.3	0.191
S6	Bread waste	Water	Acetone	$AlCl_3$; 0.148g	100.0	0.203
S7	Rice waste	Water	DMSO	$SnCl_4$; 0.289g	100.0	0.227
S8	Fruit waste	Water	DMSO	$SnCl_4$; 0.289g	50.0	0.137

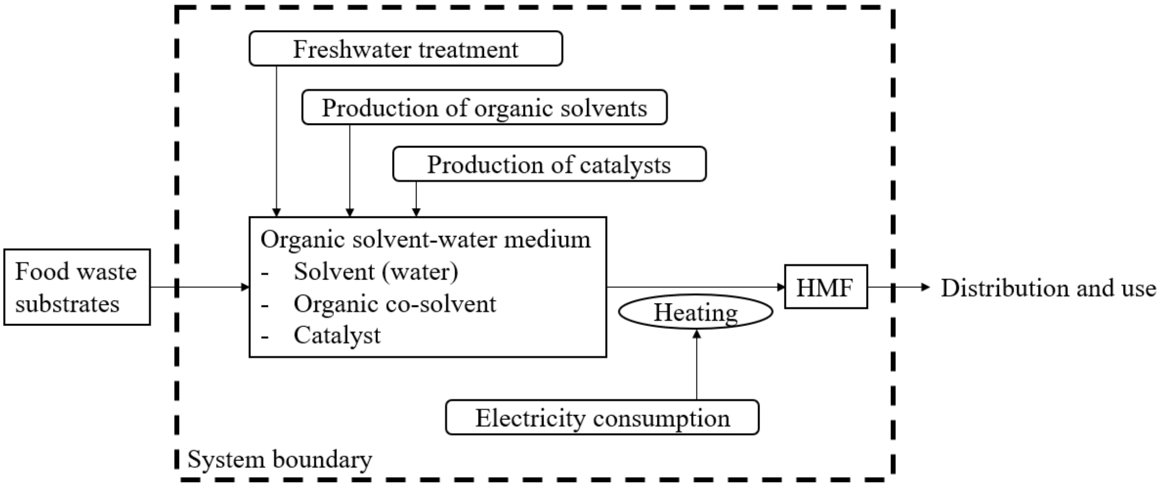
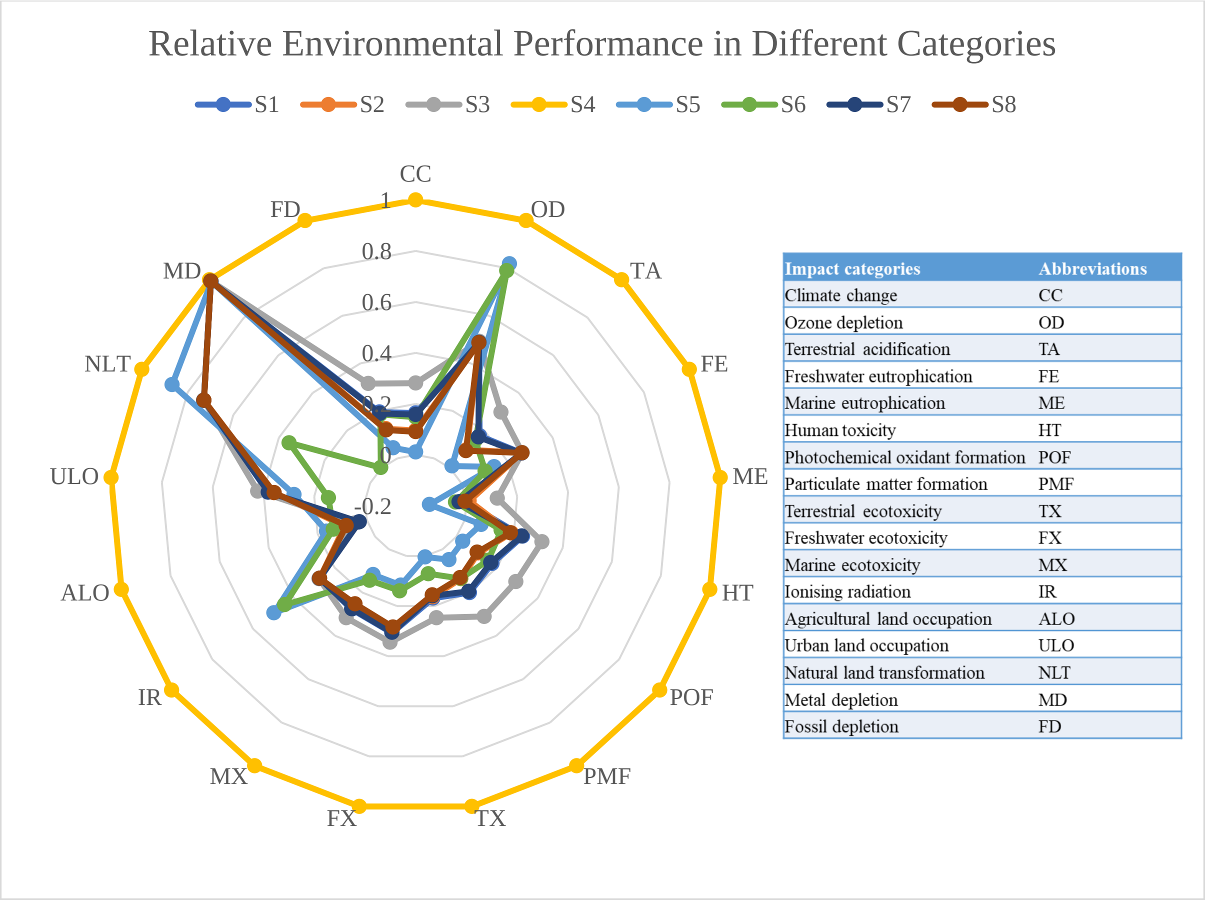


Figure 1 System boundary of food waste valorisation LCA



Impact categories	Abbreviations
Climate change	CC
Ozone depletion	OD
Terrestrial acidification	TA
Freshwater eutrophication	FE
Marine eutrophication	ME
Human toxicity	HT
Photochemical oxidant formation	POF
Particulate matter formation	PMF
Terrestrial ecotoxicity	TX
Freshwater ecotoxicity	FX
Marine ecotoxicity	MX
Ionising radiation	IR
Agricultural land occupation	ALO
Urban land occupation	ULO
Natural land transformation	NLT
Metal depletion	MD
Fossil depletion	FD

Figure 2 Relative environmental performance in LCA categories

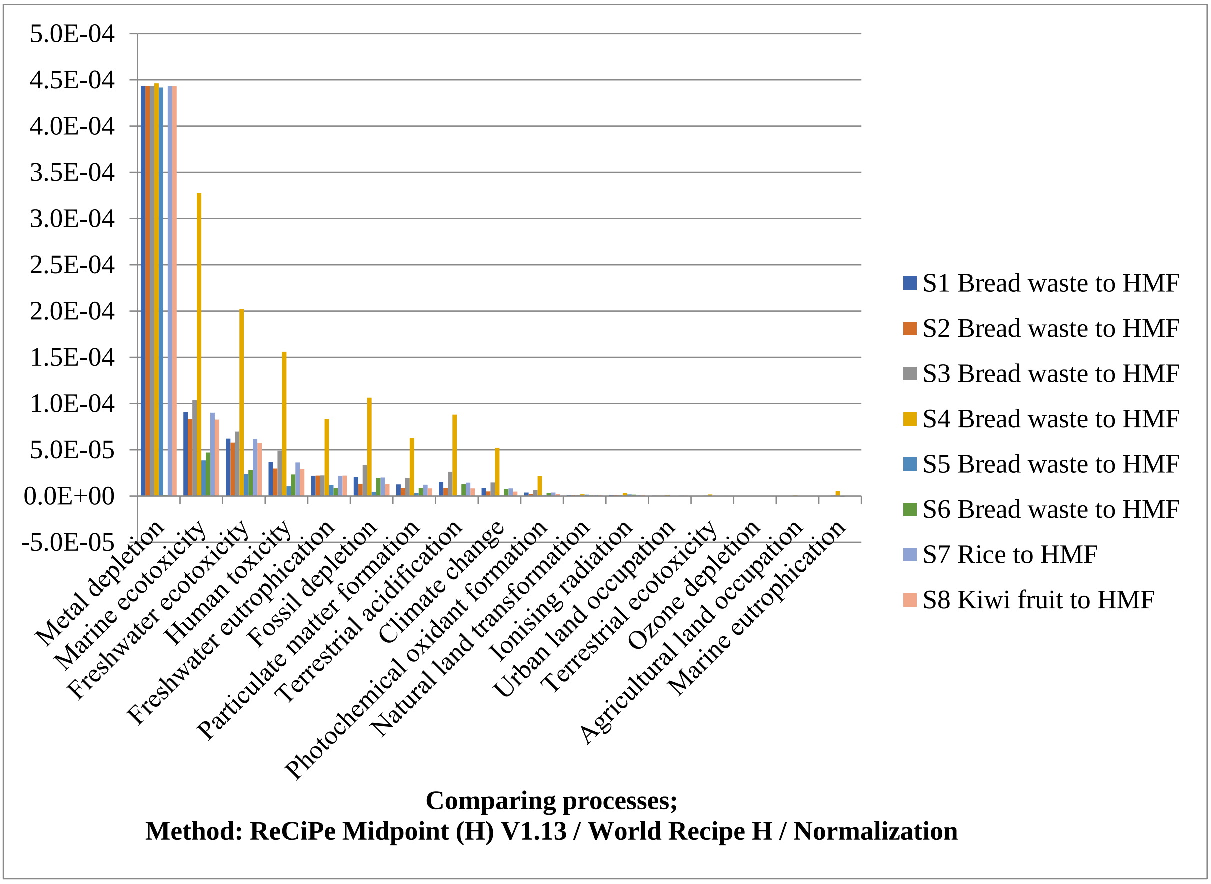


Figure 3 Normalized LCA results

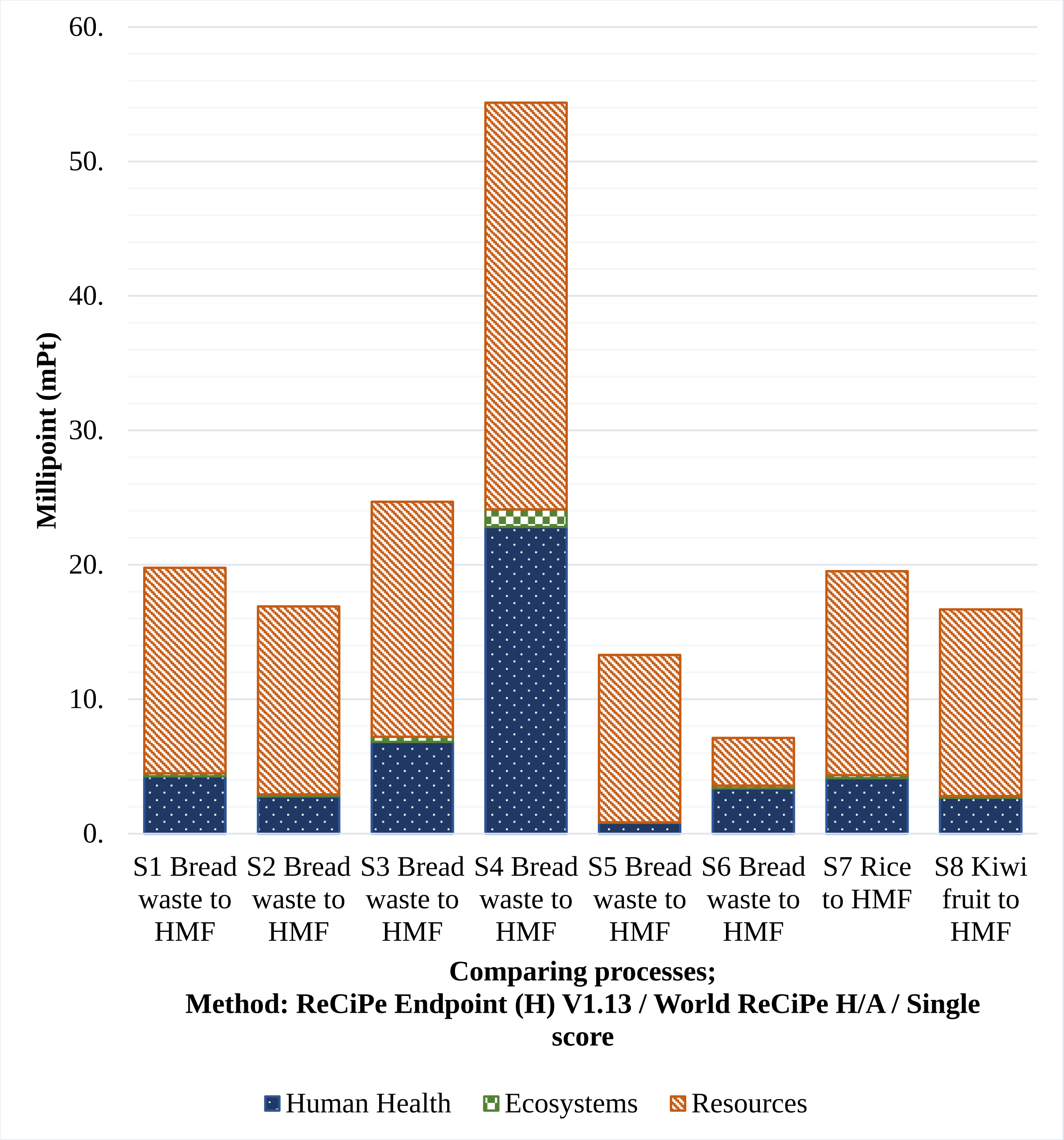


Figure 4 Single score LCA results

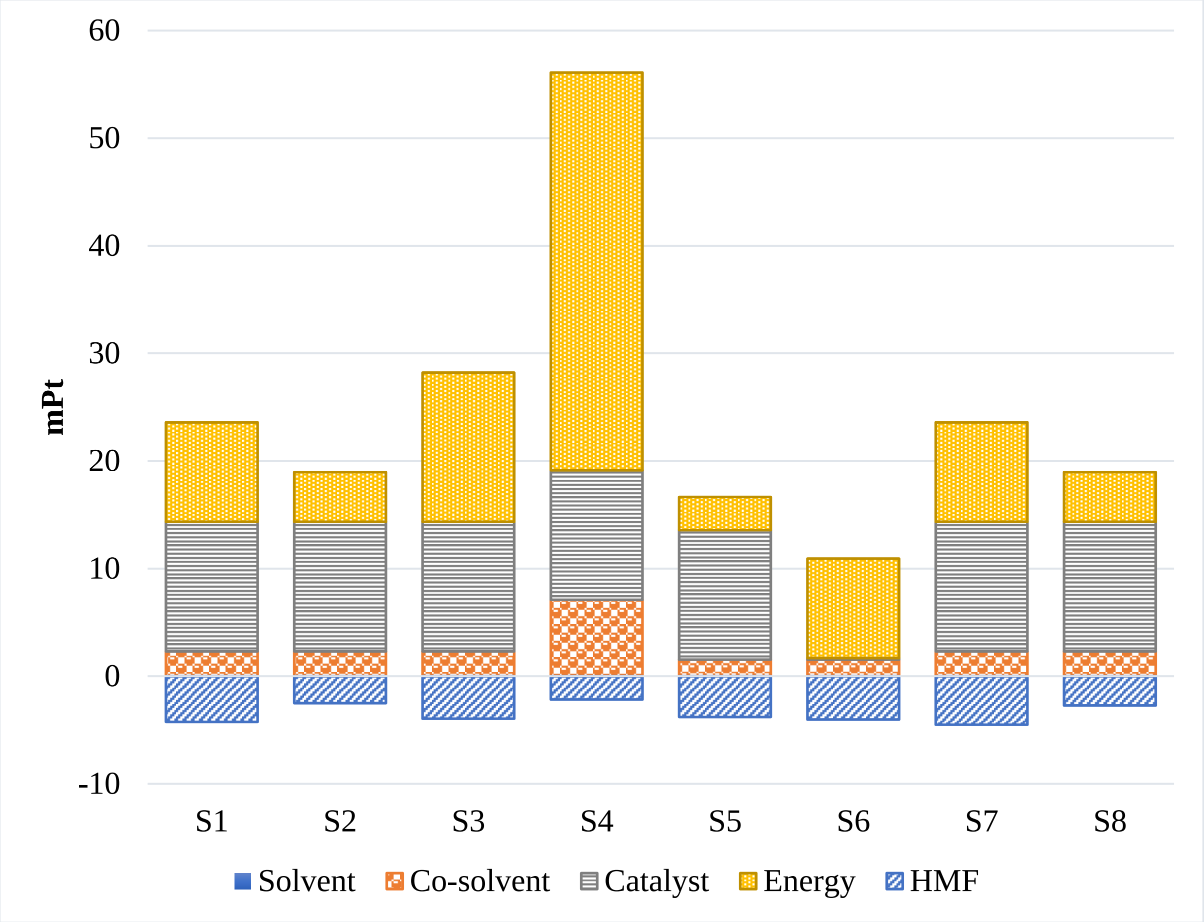


Figure 5 Process contributions to LCA results