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Comparative Assessment of Rice Mill Waste Utilisation Management in Malaysia Using Integrated Material Flow and Life Cycle Analyses

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ABSTRACT

Empty and partially filled grain (EPFG) from rice milling factories is usually discarded to landfill. Converting EPFG to valuable products could increase the waste value, improve Malaysia's rice milling waste management, and prevent environmental problems. Utilising the existing and accessible technology in rice mills factories, the optimal waste management practices involving EPFG were investigated. The options were option 1 as biochar, option 2 as compost, and option 3 as bioethanol. Data was obtained from a previous study based on the current Malaysian scenario. A methodology integrating MFA and LCA was applied to observe the environmental performance of these options, which was performed using STAN2 and SimaPro 9.0 software. The best environmental performance was found for the conversion of EPFG to compost (option 2) since less input was used and fewer emissions were released. A total of 3,550 kg CO_2 eq. per ton of EPFG used was obtained while avoiding fertiliser products. Therefore, converting EPFG to compost as an easily applied technology can be suggested to rice mill factories to improve their waste management. When deployed in agricultural waste management systems, the integration MFA-LCA model could be referred to as a useful source when implementing policies and industrial uptake.

Keywords: agriculture biomass, life cycle analysis, material flow, paddy waste, recycling.

INTRODUCTION

Common wastes generated through the paddy supply chain are rice straws and rice husks, which can be repurposed for the production of valuable products (Shafie et al., 2014; Zakaria et al., 2023). In Malaysia, rice straw is used for mushroom production while rice husk is used as fuel for boilers in rice mills (Rosmiza et al., 2019). However, another type of rice industrial waste left untapped is damaged rice grain. Milling factories are considered to have lost food if grain has suffered damage or if empty and partially filled paddy grain (EPFG) is produced because their undesirable attributes make them unsuitable for normal use and consumption (Abu Bakar et al., 2022). Grain losses often occur due to harvesting at incorrect stages of maturity, physical damage, contamination of microorganisms, inefficient drying, and improper storage conditions (Hassan and Saba, 2018). Additionally, climate changes have affected the rice ecosystem, contributing to the increased production of damaged grain (Firdaus et al., 2020).

Landfills are the traditional sites for waste disposal, but this approach creates various problems that damage the environment, like polluting the air and causing soil to deteriorate. Even though these wastes are high in nutrients, energy, and organic compounds, they are not properly managed or exploited as valuable products. This causes the loss of a potential natural feedstock for use in industry. Exploiting this waste as a feedstock for valuable products would ensure a more sustainable and environmentally friendly waste management system in the rice industry, as opposed to the conventional 'take-make-dispose' system. With emerging technological innovations, converting damaged grain into a valuable community product could be a promising economic lever for Malaysia. Products with added value like biofuels, biochemical products, and animal feed can be obtained using the chemical components obtained by the transformation of EPFG, which are comprised of cellulose, lignin, and hemicellulose (Rathnayake et al., 2018; Tursi, 2019). Adding value to the biomass is an approach employed under the circular economy framework and promoted in the move towards sustainability.

Several studies in Malaysia have investigated the conversion of rice mill waste for bioenergy, mainly for heat and energy production (Atan et al., 2018; Nazari et al., 2019; Shafie, 2015). Recently, rice mill waste has been proposed for sugar production as an intermediate for bioproducts (Abu Bakar et al., 2022). However, other forms of EPFG management that could be implemented by millers and have less impact on environmental performance have not yet been discussed. Managing bioprocessing sustainably can involve using types of bioresources, particularly types of biowaste, to produce commodities in a cost-effective way, and there is an environmental effect of the process overall (Usmani et al., 2021). Biomass-derived products have always been reported to mitigate environmental effects. Therefore, it is necessary to study bio-based product environmental loads as a platform for resolving environmental issues. Tools to manage the environment - like material flow analysis (MFA) and life cycle assessment (LCA) - can be used to ascertain the impacts of the biobased materials obtained using waste composed of biomass.

As a tool, LCA can be deployed to assess the impacts on the environment that are linked to particular products or services, which is achieved by focusing on an item's full cycle of life from the extraction of raw materials to its management at the end of its life. In addition, using LCA can enable the identification of the flow process that contributes significantly to these impacts (Catalan and Sanchez, 2020). ISO standards state that the effects on the environment of specific products, as well as any byproduct created during their manufacture, need accounting for (Uihlein and Schebek, 2009). In some cases, the impacts of byproducts can shift the balance concerning the overall environmental implications of the primary product. Therefore, these assessment findings should assist those responsible for making decisions to use scientific principles to conduct transparent analyses and comparisons of how methods of EPFG waste management perform environmentally.

In this study, a combination of two systems-based methodologies using MFA and LCA was employed to quantitatively evaluate different scenarios of EPFG management. The integrated methodologies can provide more information about the environment and the material impacts of possible system changes. Three types of EPFG utilisation systems were selected based on the ready technology uptake for millers in Malaysia, in comparison to the traditional practice of rice mill waste management. The novel contribution of this study is the application of an integrated MFA-LCA approach to evaluate rice mill waste management at the meso-level and thoroughly estimate EPFG flows through a different system using an accessible national dataset representing the country's data.

Goals and scope of the study

The aims of the current work were to, first, obtain in quantified terms the mass balance of the EPFG management system models that could be used in Malaysia and, second, undertake a quantitative evaluation of how the existing management practices and various alternative systems affect the environment. A combination of MFA and LCA methodologies was applied to obtain these goals. As a systematic tool, MFA can enable a greater spatial and temporal comprehension of the routes taken by any material or material stock that flows into a recycling site (Ghani et al., 2018; Thushari et al., 2020). Next, LCA was deployed to assess how the chosen systems of EPFG management affected the environment. The scope of the study is cradle-to-gate and involves four different scenarios of EPFG management, including obtaining value-added products. The focus of this research was the selection of options related to management that should limit how EPFG utilisation impacts the environment. A further objective was to make recommendations to the paddy industry in Malaysia regarding management practices that could be implemented sustainably. The functional unit associated with the different management systems is 1 ton of EPFG input.

Description of management options

EPFG is a starch-lignocellulosic biomass that can potentially be converted into valuable products. The composition of EPFG is as follows: 14% starch, 32.8% cellulose, 18% hemicellulose, and 16% lignin, thus making it a potential feedstock to be used for conversion to marketable products (Abu Bakar et al., 2022). Furthermore, the exploitation of EPFG to produce marketable products can be an excellent economic lever for developing countries by, for example, increasing manufacturing exports, spurring investment, creating jobs, and providing environmental protection (Tursi, 2019). Four different EPFG management options were used in this study, as shown in Figure 1. The details of the options are discussed in the description section.

EPFG management base case: EPFG dumping to landfill

EPFG dumping to landfill represents the actual scenario (base case) of EPFG management. Harvested paddy undergoes several processing steps in a rice milling factory to obtain high-quality paddy seeds. The milling process removes EPFG from high-quality seeds to ensure pure genetics and quality seed production. The waste may increase due to poor drying methods, mechanical damage during milling, and poor storage. According to an interview with a Malaysian seed producer, the EPFG removed during the milling process accounted for 6–25% of the total harvested paddy yield received in one milling factory (Kamaruzzaman, M., personal communication, 2 Jun 2017). The EPFG collected from the rice milling factory was sent to a conventional landfill site with no treatment. The distance from the EPFG collection point to the landfill was a 50 km round trip.

EPFG management option 1: EPFG conversion to biochar

In option 1, the conversion of EPFG to biochar was performed using pyrolysis technology. The pyrolysis process of EPFG was based on the study by Mohammad Hariz et al. (2019). No pretreatment was performed on the EPFG prior to pyrolysis. Feedstock wood is used as a start-up material to ignite combustion. The biochar from EPFG was produced in a retort kiln using a slow pyrolysis technique for 6–8 hrs. The traditional method of slow pyrolysis produces white smoke and EPFG biochar. In this study, the smoke from the combustion was trapped to produce pyrolysis acid (bio-oil) as a byproduct to be used in agriculture.

EPFG management option 2: EPFG conversion to compost

In option 2, EPFG was converted to compost, as performed in a study by Abu Bakar et al. (2017) and Abdul Rahman et al. (2020). To ensure an efficient composting end-product, the EPFG was mixed with goat dung at a ratio of 2:1.

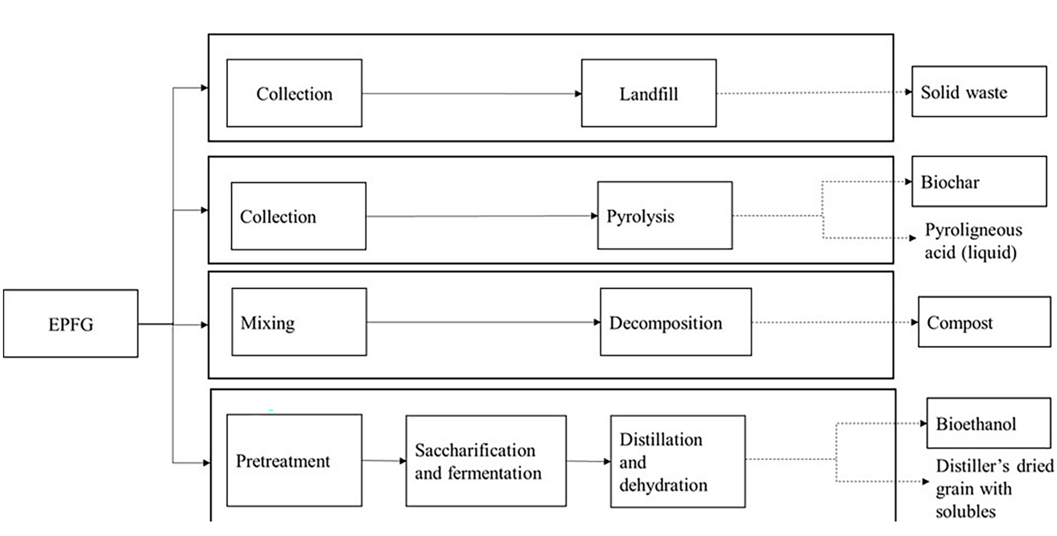

Figure 1. System boundary of EPFG management options proposed

The passive aeration approach was used to conduct the process of composting, which involved a heap 1.5 m tall. The mixture was allowed to enter the composting stages until the curing phase. The maximum composting temperature was obtained at 65 °C during day 6, indicating that the process was entering the thermophilic phase. As the phase of curing continued, the temperature of the compost began to fall towards ambient, which implied the imminent stabilisation of the organic material. Overall, the composting process was performed for a total of 60 days. The compost produced could be used in agriculture as a substitute for fertiliser.

EPFG management option 3: EPFG conversion to bioethanol

Option 3 involved the conversion of EPFG to bioethanol. The process in option 3 followed the work of Abu-Bakar et al. (2023) and Mohd Yusof et al. (2019). The EPFG was ground using a hammermill to reduce the feedstock particle size prior to pretreatment. Further processing of the bioethanol produced from the EPFG involved a separate hydrolysis and fermentation method. The EPFG, having been ground, was hydrothermally pretreated at 120 °C for 60 min, after which glucose was produced through enzymatic hydrolysis. With nitrogen sources of yeast and urea, the resulting glucose was subjected to fermentation to become bioethanol. Centrifugation was then utilised to separate the solids and liquids in the broth of fermentation. Additional purification of the bioethanol-based liquid was achieved by continuously distilling, rectifying, stripping, and drying using a molecular sieve, after which 98.9% of anhydrous bioethanol was obtained. The solid residue was sold as dried distiller grains with soluble (DDGS).

MATERIALS AND METHODS

Inventory analyses

The input and output data collected was based on the description mentioned in Section 2.2, the Description of Management Options. The data collected was based on previous studies of agriculture residue management in Malaysia (Abu-Bakar et al., 2023; Mohd Yusof, 2020; Mohammad Hariz et al., 2019; Abu-Bakar et al., 2017). In the current work, the assumption was that due to the involvement of several factors in EPFG generation, the EPFG bore the burden on the environment from the phase of cultivation. The factors involved are extreme climate conditions, crop management practices, postharvest management, and disease emergence (Hassan and Saba, 2018). These lead to uncertainty regarding the EPFG generation yield for each cultivation season. Apart from that, this study aimed to improve the EPFG management practices in Malaysia by converting EPFG to valuable products, which might increase the value of EPFG in the future. Hence, the burden from the cultivation and milling phase was considered if the EPFG gained economic value (Abu-Bakar et al., 2023).

Consideration was given to several crucial environmentally focused interventions, including the use of particular materials and utilities; air emissions like particulates of CO_2, SO_2, NO_x, N_2O, and CH_4; as well as water emissions like COD and BOD. The sources of the inventory data for the background processes relating to electricity generation, water supply, and chemical production were based on the Ecoinvent database v3.0. The sources of data are presented in detail in the Supporting Information section. The conversion of EPFG to other products, as indicated in options 1, 2, and 3, was assumed to occur within the rice milling processing factory area. This would ensure the factory was used at maximum capacity as a decentralised processing facility. The burden from farming and processing was given to EPFG at a 20% mass allocation (Abu-Bakar et al., 2023). Additionally, no allocation was performed for the option that generated co-products in the system boundary. The inventory analyses of the EPFG management were conducted using STAN v2.6.

Life cycle impact assessment

The LCA methodology follows the 'ISO 14040: Principles and Framework' and 'ISO 14044: Requirements and Guidelines for International Environmental Standards' (ISO 2008). The characterisation model of the CML baseline v3.05 after incorporation into the SimaPro v9.0 software was used to obtain the life cycle impact assessment (LCIA) findings. The following impact categories were explored in this work, based on the CML methodology: global warming potential 100-year time horizon (GWP; measured in kg CO_2 eq.), abiotic depletion (AD; measured in kg Sb eq.), eutrophication potential (EP; measured in kg PO_4 eq.), acidification potential (AP; measured in kg SO_2 eq.), human toxicity (HT; measured in kg 1,4 DB eq.), and photochemical oxidation potential (POP; measured in kg C_2H_4 eq.).

Sensitivity analysis

Sensitivity analysis is deployed to determine how to apportion a model's output variations to different variation sources in the parameters inputted (Muñoz et al., 2014). A one-at-a-time approach analysis of the product yield was performed to further understand how the possible EPFG management would affect the environmental performance. Percentage changes from the baseline were used to observe the change of input variables chosen at +/-10% (Liu et al., 2021). This choice of data enabled a comparison of every impact category, with the same scale used in these situations.

RESULTS AND DISCUSSIONS

Material flow analysis

The MFA is presented in Figure 2: (a) base case, (b) option 1: EPFG conversion to biochar, (c) option 3: EPFG conversion to compost, and (d) option 3: EPFG conversion to bioethanol. Overall, 4 t/a of harvested paddy grain collected was estimated to remove 1 t/a of EPFG as waste. As shown in Figure 2a, the EPFG was sent to landfill as open dumping, releasing emissions and leachate into the atmosphere. The model in the base case shows that from 1 t/a of EPFG, 0.86 t/a EPFG was still present over time, with the balance released as emissions. The open dumping of EPFG involves the natural decaying of the organic matter. In a hot and rainy climate like that of Malaysia, this practice causes air and water body pollution due to the release of degraded products. These products generate unpleasant odours, as well as disease-carrying leachates and run-off. In option 1, the EPFG was considered for biochar production. From the model, 1 ton of EPFG produced 0.32 tons of biochar and 0.05 tons of pyroligneous acid. The carbonisation temperature was at 500 °C, causing a loss in biomass weight and the release of water vapour from the biomass. In the biomass, both the free and absorbed water were precipitated via this process. As the temperature increases, water vapour forms along with carbohydrate decomposition (Cheng et al., 2022). In this study, the water vapour was condensed to form pyroligneous acid. The release of emissions was due to carbonisation. Nevertheless, biochar production from biomass could act as an amendment for carbon sequestration and lead to more significant environmental benefits in the future.

In option 2, EPFG was proposed for compost production. An appropriate C/N ratio formulation is required to ensure successful composting. Adding goat dung would be a good nitrogen source in the degradation of EPFG, leading to an ideal initial C/N ratio at 25:1 in the compost (Abdul Rahman et al., 2020). After 60 days, the compost is at maturity with C/N ratio at 12:1. In this study, 1 ton of EPFG yielded 0.69 kg of compost, leaving a balance of losses and emissions. Losses as output from the process were due to the degradation of carbohydrate composition into stabilised materials. The composting process involves microbial metabolism for organic material decomposition (Abu Bakar et al., 2017). Thus, as a lignocellulosic feedstock (containing cellulose, hemicellulose, and lignin), EPFG could be decomposed into simpler carbohydrates by microorganisms and subsequently be used. This would lead to mass loss. Moreover, various parameters - such as mixing, aeration, temperature, C/N ratio, and microbial inoculum usage – can influence the composting process, which could enhance the degradation process.

Correct techniques should be constantly emphasised to ensure the production of quality compost from biomass. For instance, the quality of compost can vary depending on factors like the materials used and the composting method employed. Poorly managed compost piles may not reach optimal temperatures or may not decompose properly, resulting in compost that lacks essential nutrients or contains harmful pathogens. Additionally, a balanced C/N ratio is crucial for effective composting, as too much carbon can slow down decomposition, while too much nitrogen can lead to odors and nutrient loss. Another significant concern is the potential dispersal of weed seeds through the composting process. While composting temperatures can reach levels that kill many weed seeds, some hardy ones may survive and germinate when the compost is applied to soil, leading to weed infestations. Hence, maintaining the right balance of compost raw materials and techniques requires careful monitoring and

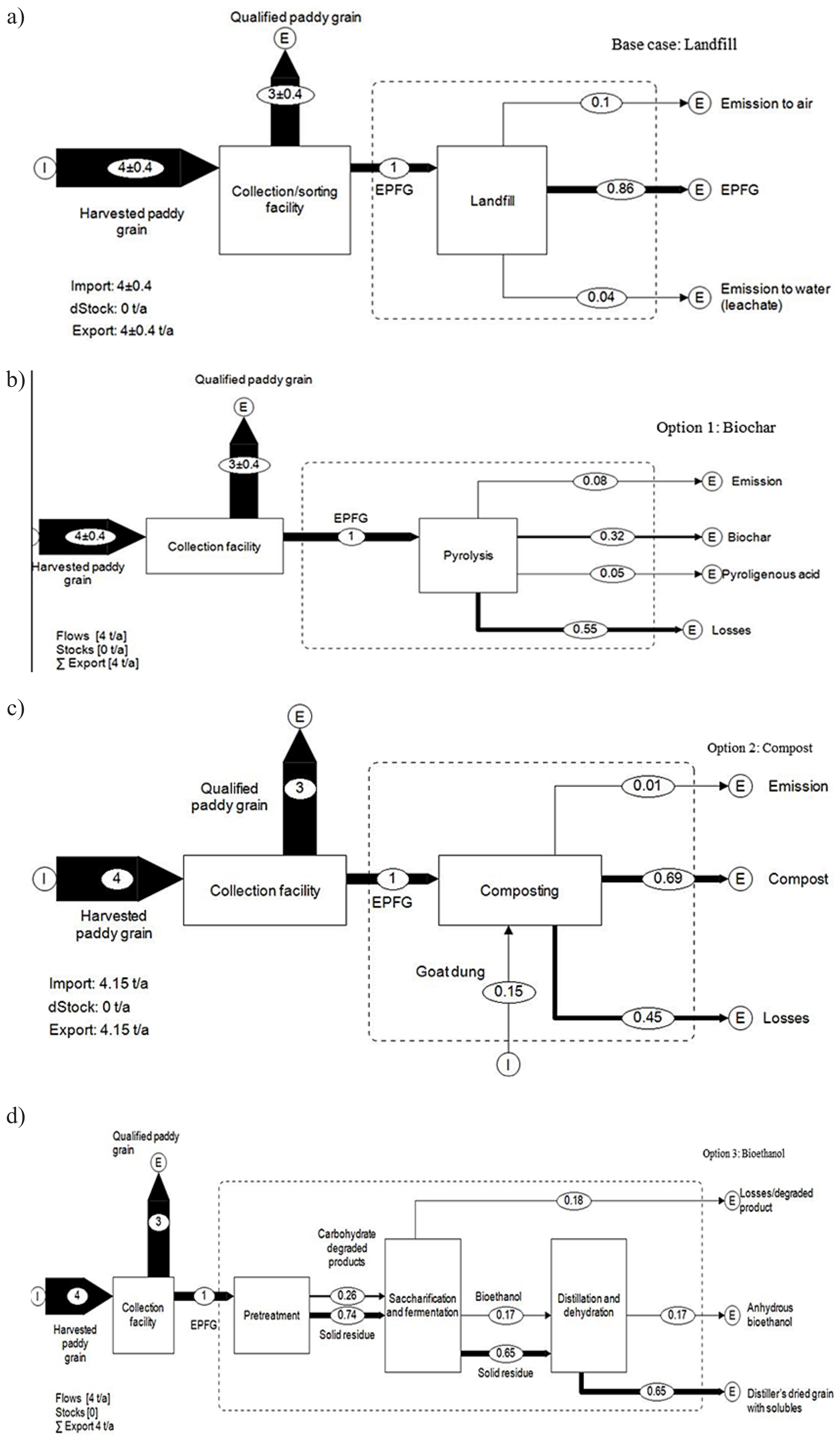

Figure 2. Material flow analysis of EPFG management options for (a) base case, (b) option 1, (c) option 2, and (d) option 3. Remarks: I, import flow; E, export flow.

adjustment, as fluctuations can impact the quality and usability of the compost.

Various Malaysian government policies have endorsed the utilisation of agricultural residues as renewable resources for producing valuable products. Hence, option 3 was proposed in this study. The conversion of EPFG to bioethanol involved 1) pretreatment, 2) saccharification and fermentation, and 3) distillation and dehydration. One ton of EPFG yielded 0.17 tons of bioethanol and 0.65 tons of DDGS. The EPFG was pretreated using hydrothermal pretreatment to obtain C6 and C5 sugars in liquid form. The solid and liquid residue mixture was subjected to saccharification and fermentation to produce bioethanol. So that the ethanol could be further purified, the supernatant with the bioethanol was subjected to a system that caused it to be continuously distilled, rectified, and stripped. The system involved drying with a molecular sieve so that the water could be separated further, which resulted in 98.9% of anhydrous bioethanol. The solid residue can be sold as DDGS, a high-value animal feed product (Mohd Yusof, 2020).

Comparative assessment of base case with options 1, 2, and 3 of EPFG management-inclusive of avoided product

A comparative assessment was performed on the base case with options 1, 2, and 3, and this is presented as normalisation data (Table 1). Indisputably, the highest potential environmental loads were related to landfills compared to the EPFG management options. The negative values for the potential environmental impacts reflect an avoided environmental impact (Pop et al., 2017). If a paddy milling factory fails to handle waste properly, the environment becomes polluted because wastes rich in organic loads, nutrients, and solids are generated. The main contributor to landfill was emissions released into the air and water bodies. Removing EPFG to landfill without proper management causes anaerobic decomposition, producing landfill gas and leachate. An estimated 90% of the organic carbon from EPFG is emitted into the air as methane (CH_4) and CO, while the remainder is considered to be released as leachate (Binner, 2003). CH_4 gas formed the highest emissions released into the air due to the anaerobic decomposition of EPFG in the landfill.

Moreover, the chemical oxygen dissolved (COD) was estimated at 1.19×10^{07} kg per ton EPFG (Saheri et al., 2012). It has been reported that waste from paddy milling factories does not contain toxic materials; however, it does have enough nutrients and pesticides, leading to eutrophication and groundwater pollution (Karunaratne, 2011). Hence, based on the normalisation data, eutrophication from landfills is the worst impact category, with a contribution of 88%, followed by the impact of GWP at 10%. The other impact categories for landfill were less than 1% for the normalisation data.

Environmental performance of options 1, 2, and 3 for EPFG management decisions

This study focused on incorporating an effective waste management system into factories to facilitate a sustainable development approach for handling EPFG. A growing volume of research has been carried out to address agricultural waste by exploring biomass and converting it into value-added products such as biofuel, biochemicals, and biopolymers (Duque et al., 2021). Converting agriculture waste into bioproducts could increase its economic viability and provide further environmental benefits (Liu et al., 2021). In proposing a sustainable EPFG management approach, three scenarios were considered based on the potential biomass conversion practices in Malaysia, which are option 1: EPFG conversion to biochar, option 2: EPFG conversion to compost, and option 3: EPFG conversion to bioethanol. The relative contribution and impact of managing 1 ton of

Table 1. Comparative assessment of impact categories in Options 1, 2, and 3

Impact category	Base case	Option 1	Option 2	Option 3
Abiotic depletion	2.00×10^{-12}	-7.72×10^{-12}	-1.72×10^{-11}	-1.05×10^{-10}
Global warming potential	3.21×10^{-05}	1.24×10^{-09}	7.07×10^{-10}	7.44×10^{-10}
Human toxicity	1.09×10^{-08}	5.89×10^{-10}	3.29×10^{-10}	9.68×10^{-10}
Photochemical oxidation	3.99×10^{-06}	2.13×10^{-10}	1.32×10^{-10}	-1.05×10^{-10}
Acidification	1.08×10^{-06}	2.11×10^{-09}	1.18×10^{-09}	3.37×10^{-09}
Eutrophication	2.72×10^{-04}	2.18×10^{-09}	1.20×10^{-09}	3.15×10^{-09}

EPFG are depicted in Figure 3. As previously stated, negative values indicate an environmental saving through the avoidance of emissions while positive values represent the burden of EPFG conversions on the environment.

In Figure 3, the conversion process in all the options creates environmental savings in the AD impact. The outcome of the negative value is due to byproduct emissions being avoided, with these replacing the requirement to use particular types of products that cause high emissions, like synthetic fertiliser and petrol, as with option 2 and option 3. Nevertheless, of all the options, converting EPFG to compost (option 2) was the best management approach with the least environmental burden. The compost was prepared in a heap measuring 1.5×1.5 m, and aeration was performed every 7 days (Abu Bakar et al., 2017). This reduced the formation of methane trapped in the compost heap, preventing the release of emissions.

Additionally, CO_2 released from the compost is considered biogenic and not included in a GWP estimation (Roberto, 2014). With option 2, net savings were observed for abiotic depletion and the photochemical oxidation impact. In other impact categories, relative contributions for option 2 ranged from 17% to 26%. Substituting synthetic fertiliser with compost used in agriculture creates an avoidance of emissions, thus contributing to the lower environmental impact of option 2. Nevertheless, well-managed composting operations are crucial to produce lower CH_4 and N_2O emissions (Al-Rumaihi et al., 2020).

EPFG management options on environmental impact categories

The characterisation results of the EPFG management options for all the impact categories are depicted in Figure 4. Option 1 saw the emission of higher GWP, at 6401 kg CO_2 eq., compared to options 2 and 3. The release of gas and aerosol during the pyrolysis process, apart from using EPFG as the feedstock, contributed to this impact. The emissions emitted in option 1 of this study are higher than those obtained in the study by Munoz et al. (2017). The authors reported an emission of -2590 kg CO_2 eq. of biochar from forest residue. Munoz et al. (2017) also included the avoidance of emissions from the combustion of fossil fuels in transportation and hydroelectricity, a factor not included in this study. In this study, the objective of option 1 was to utilise the material as a soil amendment in the agricultural sector, so the combustion of biochar for fuel is not included. Even though net GHG was reported in this study through carbon sequestration, the amount of biochar produced per ton of EPFG was insufficient to obtain a negative impact value. Besides that, other studies reported that the feedstock type, processing type, and pyrolysis temperature would yield different LCA results related to biochar production (Brassard et al., 2018; Mohammadi et al., 2016; Smebye et al., 2017). For the other impact categories, option 1 contributed moderately at 4568 kg 1.4-DB eq. for HT, 59.5 kg SO_2 eq. for AP, and 28.7 kg PO_4 eq. for the EP impact.

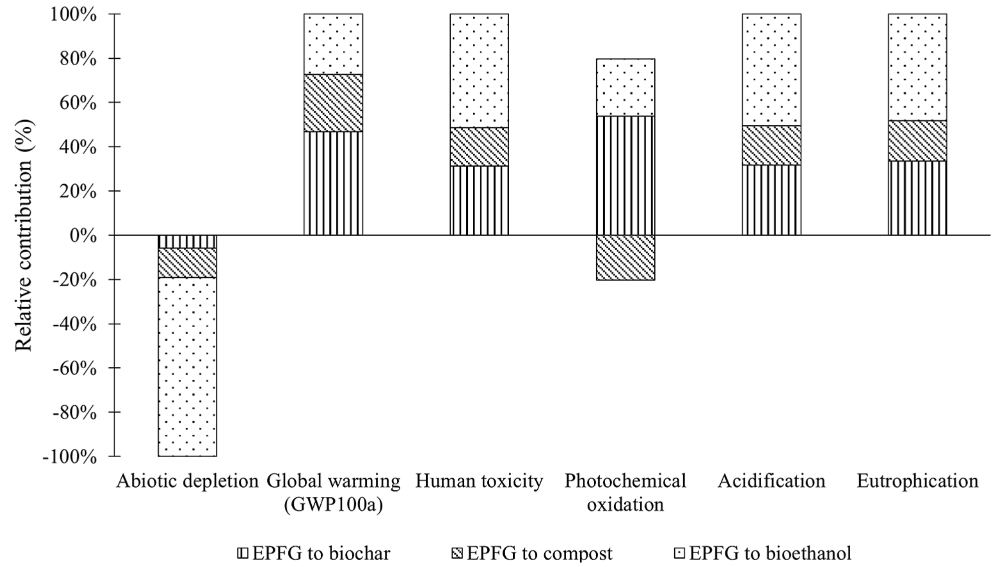

Figure 3. Relative contribution and impact of managing 1 ton of EPFG

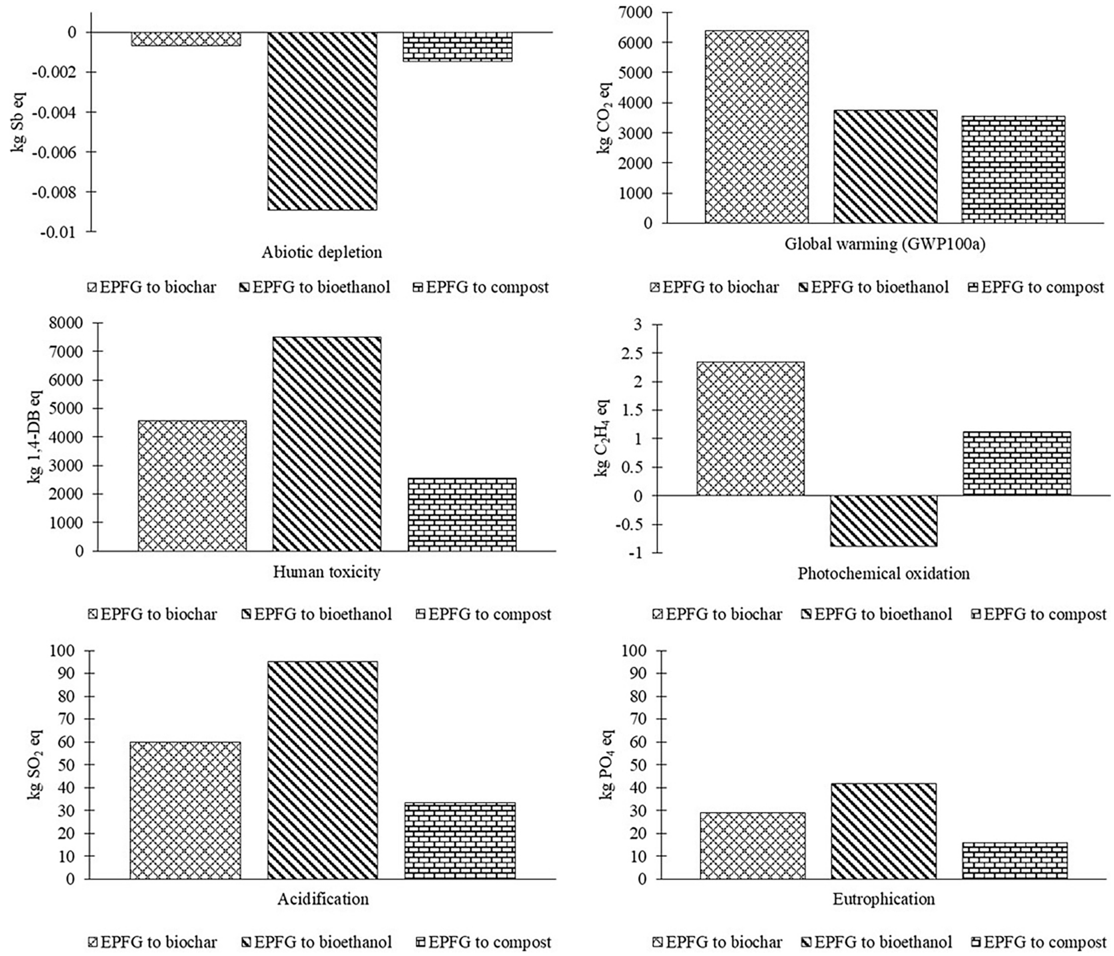

Figure 4. Characterisation results of EPFG management options (1, 2, and 3) for all impact categories

The best EPFG management was achieved through option 2, in which EPFG was converted to compost. Option 2 produced a better environmental performance for most of the impact categories analysed. In terms of the GWP impact, option 2 contributed to 3550 kg CO_2 eq., including avoided emissions from synthetic fertiliser. EPFG as feedstock was the significant input contributing to the GWP impact. After this, emissions were released during the stage of biological degradation and fuels were utilised to collect and process raw material. Diaz et al. (2018) reported that home composting emitted 4500 kg CO_2 eq. in the GWP impact. Nevertheless, the author found that through composting, energy savings from mineral fertilisation could be obtained, thus contributing to a better environmental performance than landfilling. Additionally, mitigation strategies could include further improving the environmental performance of option 2. For instance, using a bulking agent helps in enhancing the compost aeration system, as does utilising matured compost as a covering material (Chien Bong et al., 2017). The EP and AP impact results from option 2 are 15.87 kg PO_4 eq. and 33.37 kg SO_2 eq., respectively. The main contributors to this were the use of EPFG as raw materials, as well as emissions produced as part of the process of degradation while composting was occurring. Using urea and fertiliser during the agriculture phase for crop maintenance contributes towards high EP and AP impacts in EPFG biomass. The impacts of EP are substantially influenced by the input of fertiliser because of nitrate (NO_3) emissions, which run off through bodies of water and the soil.

Reductions in minerals and crude oil, as well as other non-living natural resources, are used to denote the AD impact, which is generally utilised to indicate that energy from fossil fuels is being consumed (Wang et al., 2013). The EPFG conversion to bioethanol shows substantial net savings in AD compared to options 1 and 2. Based on the MFA results, the conversion process of EPFG to bioethanol yielded a co-product of DDGS. DDGS is assumed to be used as animal feedstock in a similar way to other fermentation residues from starch-lignocellulosic biomass. Under the GWP impact category, the management of EPFG in options 2 and 3 emitted 3550 kg CO_2 eq. and 3740 kg CO_2 eq., respectively. Based on the data, the difference between each option was 190 kg CO_2 eq., contributing to the extensive process flow for producing bioethanol. Hence, more input was acquired in the system boundary of option 3 compared to composting. Nevertheless, the impact of the conversion process in option 3 was still lower than that of option 1 in the GWP category, making it a potential waste conversion for bioenergy production. Our results also agree with those of Silalertruksa and Gheewala (2013), whereby the author shows that converting rice straw into bioethanol contributed to a net saving of the AD impact category, as well as a GWP reduction of 283 kg CO_2 eq., compared to other management practices (i.e., rice straw-based-electricity and -biodiesel). Despite that, in different impact categories, the conversion process in option 3 had a higher value than the other options. Furthermore, based on the characterisation data, the main input contributing to option 3 was electricity and yeast usage for fermentation.

Sensitivity analysis

Since the models are complex and the inputs are uncertain, an LCA analyst must have an understanding of how the output of the model is affected by every potential source of uncertainty. Only in this way can effective and responsible use of the model be made within the process of making decisions (Cucurachi et al., 2022). In this study, sensitivity analysis identified how the product yield contributed directly to the burdensome environmental footprints. With technology advancements, resource recovery could be optimised. One-way sensitivity analysis was performed for each management option, based on the product recovery. The percentage changes from the baseline were used to observe the change in product yield at +/-10%, based on the normalisation results. Figure 5 shows the sensitivity results as a tornado diagram.

The results depicted in Figure 5 are presented as the significant impact categories reflected in this study. At 2%-11%, a greater burden on the environment was noted when the EPFG recovery rate fell by 10%. In contrast, the improved recovery rate of EPFG reduced the eutrophication and GWP impact categories by 8%-26%. The highest reduction was observed on the GWP impact in option 2 when a 10% sensitivity was performed. In comparison to the alternative options for management, compost was seen to perform best in terms of the environment in the categories of GWP and eutrophication, falling from the baseline by 26% and 10%, respectively. Compost production generates environmental burdens related to air emissions and diesel consumption. However, avoidance products can be generated to replace fertiliser in the market. Zhao et al. (2014) demonstrated that using compost on areas devoted to agriculture can reduce the effects on GWP, AP, ET, and HT due to the replacement of fertilisers containing N, P, and K. In their study, Larnaudie et al. (2021) also noted how product yield could significantly and positively affect environmental factors. An increase in the yield of bio-ethanol was found to correlate with a reduction in the effects on the environment due to the maintenance of the value of the input conversion. Thus, the indication is that when each process variable remains stable, the process becomes more efficient, and the resulting higher product yield means the impact on the environment is reduced.

Barriers to adoption and conceptual framework of agriculture waste management in Malaysia

Improper waste handling and management in milling factories can cause environmental concerns and the depletion of natural resources. According to Food and Agriculture Organisation (FAO), the postharvest loss in milling factories is food loss and could account for up to 50% of the available food (FAO, 2020). Such waste is characterised as organic waste and it is biologically unstable, so it could harm the environment if not handled properly. These wastes are high in nutrients, energy, and organic compounds, but they are inadequately managed and could be exploited to be recovered and reused as valuable components. Malaysia has been promoting the commercialisation of valuable products, mainly those derived from palm oil. The abundance of palm oil wastes and their potential value for boosting Malaysia's economy has been widely introduced and practically applied in industry. However, other agricultural residues are still under investigation for their commercialisation potential. Implementing a circular economy could utilise the abundance of agricultural waste from various sources and convert the linear supply chain into closed-loop cycles, thus contributing to the concept of sustainability. When producing value-added products using waste from

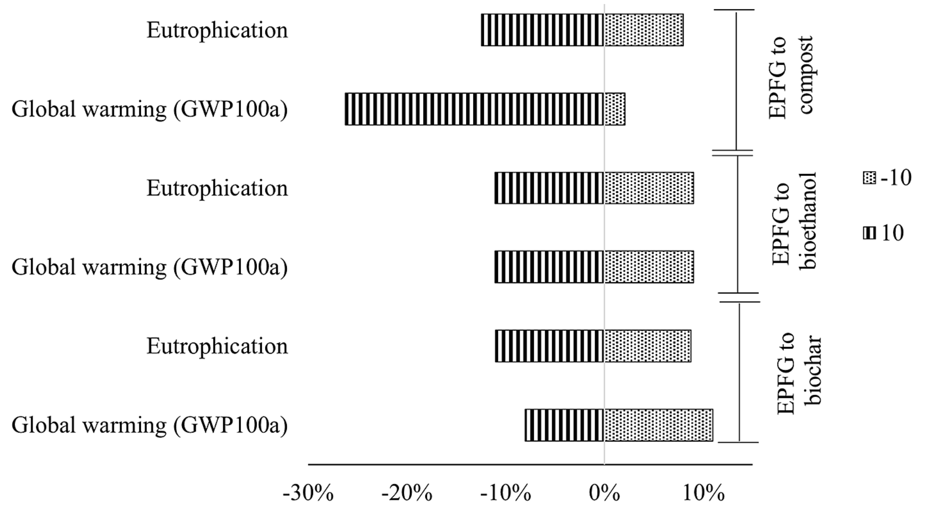

Figure 5. Sensitivity analysis of product yield from options 1, 2, and 3 at ±10% from the baseline

the paddy industry, the usual focus is the straw and husk of the rice. Moreover, too little data is available on how waste from seed processing can be bioconverted. Additional studies are needed to determine how value-added products with different effects on the environment can be maximised in terms of their output. Therefore, several barriers must be discussed to ensure successful sustainable paddy waste management strategies in Malaysia. For instance, technical challenges include technological barriers and the lack of technical professionals. Malaysia has been focusing on the conversion of palm oil biomass to higher-value products (such as bio-chemicals, biofertiliser, and bio-composite). However, other underutilised biomass is also recovered for low-value utilisation (How et al., 2019). Meanwhile, the majority of biomass conversion technologies are foreign imports because locally developed advanced valourisation technologies are unavailable. This leads to high capital and maintenance costs, making the adopted technologies inaccessible to small and medium enterprises in Malaysia (MiGHT, 2023). To make matters worse, the imported technologies were not designed for the local agricultural biomass, which may lead to incompatibility and/or low recovery rates. Agricultural waste disposal systems rely on the chemical and physical characteristics of the collected agro-waste materials. Converting waste derived from agricultural activities into any valuable product is affected by the actual biomass composition. The composition of agriculture biomass consists of cellulose, hemicellulose, lignin, starch, protein, and ash. Understanding the properties and composition of biomass is important to evaluate the suitability of the conversion process technology.

Furthermore, various environmental protection rules and regulations have been enacted to guide agricultural waste disposal systems. Some selected disposal systems are used more often than others for various reasons, such as disposal cost, environmental friendliness, waste qualities, and basic demands for future waste utilisation. For instance, many waste disposal operators practice landfilling as it is cheap and waste is easily discarded (Tosiah, 2021). Nevertheless, additional environmental issues arise from these practices, including odours, pollution of groundwater, toxic emissions, and leachate. In contrast, some agricultural wastes are managed through incineration. This involves a thermochemical process that combusts waste with oxygen at high temperatures. Although this may seem a promising approach for managing agricultural waste, most incineration processes lack sustainable technology measures, releasing air pollution (Lee et al., 2022). Composting is another prominent approach for managing agricultural waste. The process involves waste degradation by microorganisms, producing valuable soil conditioners for agricultural purposes. Composting could be performed like home-composting to a much larger extent, such as in industrial composting. Recent scholars have identified the attraction of using as a waste disposal approach involving the use of biomass refining to recycle agricultural waste and develop high-value products. The refining process relies on the availability of feedstocks, biomass chemical composition, and technology to allow efficient processing for the development of value-added products. The approach is among the strategies within the circular economy that add value to biomass resources, lower GHG footprints, reduce reliance on fossil fuels, and include the valourisation technologies of biomass and waste materials from numerous resources (Leong et al., 2021). Based on this discussion, a conceptual framework of sustainable agriculture waste management is presented in Figure 6.

Through various policies, the Malaysian government has supported the potential use of agricultural residues as renewable resources for making valuable products. Moreover, recent research on agricultural residue use has been encouraged due to concerns about the limitations of fossil-based resources, environmental issues, sustainable practices, and consumers' preferences for natural products with the qualities of biodegradability and environmentally friendliness. Biomass recycling has been conducted since the Eighth Malaysia Plan (2001–2005), but in the intervening period, greater focus was directed to renewable energy as a fifth type of fuel and supplies of conventional energy sources that would supplement the existing stocks. From that point, the commercialisation of products from biomass and new products from biotechnology was accelerated in the Ninth Malaysia Plan (2006–2010), Tenth Malaysia Plan (2011–2015), and Eleventh Malaysia Plan (2016–2020). In addition, the National Solid Waste Management Policy was introduced in 2006. The policy established a comprehensive, cost-effective, and sustainable waste management framework that involved using affordable technologies using the 3R activities (Agamuthu and Dennis, 2011). In 2012, The introduction of the Biomass Industry Strategic Action Plan was intended to assist Malaysian small and medium enterprises to achieve high-value utilisation through the exploitation of the biomass resources available locally (MiGHT, 2023). Additionally, a set of government initiatives were established to incentivise local investment in biochemical facilities with the aim of enhancing biomass industrial development as part of the National Biomass Strategy 2020 (AIM, 2020). In the Twelfth Malaysia Plan (2021–2025), under the strategy of realising the potential of the biomass industry, the Malaysian government encouraged the biomass industry to shift from low-value to high-value bio-based products through research, development, commercialisation and innovation.

Through the National Sustainable Consumption Production (SCP) Blueprint, three key aims – the expansion of the economy, safeguarding of the environment, and inclusiveness in society – would be coordinated as part of a concept of developmental integration so that green growth could be achieved. The idea behind the SCP is to promote economic expansion while avoiding environmental damage and risk to future generations' needs. The SCP Blueprint and the agenda for Sustainable Development Goals are therefore aligned, with reliance now placed on an innovative paradigm that integrates methods, tools, and frameworks within the circular economy. Sustainable-focused decisions can be enabled by using

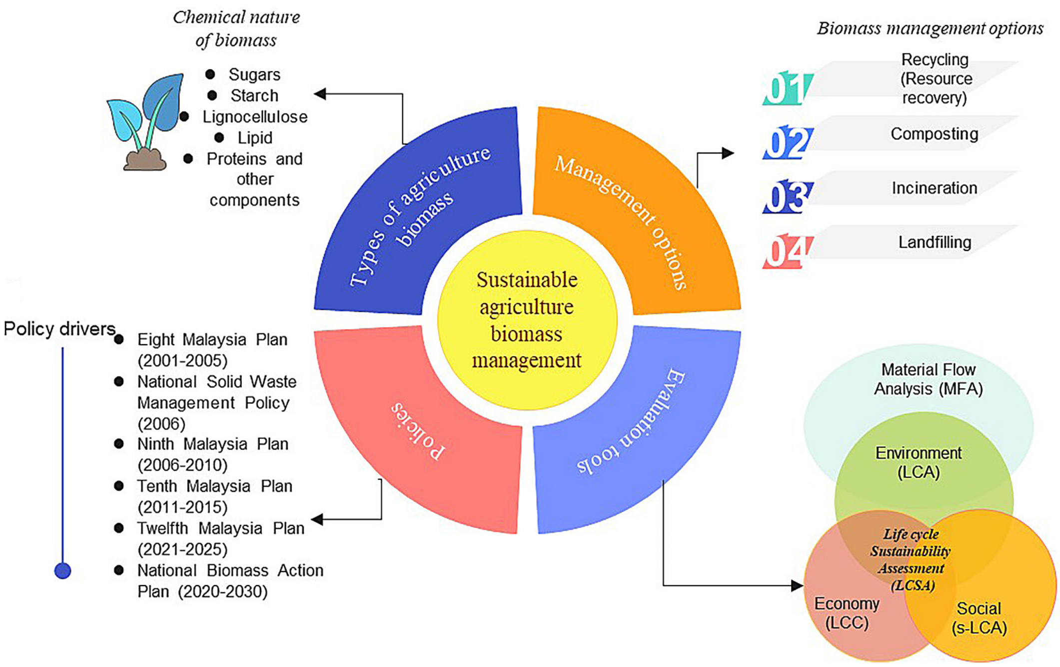

Figure 6. Conceptual framework of sustainable agriculture waste management

the specific environmental management framework of LCA (Corona et al., 2019). Sustainability assessment is included to offer any decision-maker a measurement of short- and long-term perspectives on integrated systems of nature and society that apply to both the global and local scales, as well as help them decide the actions to take or avoid so that sustainability is achieved in society (Ness et al., 2008). This assessment also considered the social and economic aspects of sustainability decisions. Practitioners have conducted integrated modelling using MFA and LCA as part of material management strategies. The value of MFA is that it measures a material's flows and stocks within clear boundaries and for a set time (Laner et al., 2016). The model integration approach develops strategies to optimise material flows and environmental impacts. This could involve redesigning products or processes, improving resource efficiency, or implementing waste reduction measures. In return, the model integration would improve the consistency of outcomes, offer more information value, and provide a stronger foundation for decision-making.

CONCLUSIONS

In the current study, Malaysia's EPFG management options are examined so that the paddy waste industry's existing practices can be addressed using the integration of the MFA-LCA models. Three options were proposed, consisting of composting and recycling resources. In the MFA results, 1 ton of EPFG was converted into three management options yielding different end-products. The most valuable product from the EPFG was observed in the composting process. The potential for sustainability management of agriculture residue waste was observed through the bioconversion route for compost and bioethanol production. The most emissions released were when dumping EPFG to landfill. The landfilling management system had a high environmental impact burden due to the release of emissions. To avoid this issue, processes related to net environmental benefits such as incineration, composting, and resource recovery should be implemented. The emission estimation results and potential impact categories from this study could guide further processes of biomass conversion into other value-added products. Hence, this study and its results should provide a basis for improving paddy waste management.

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