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Life Cycle Assessment of Fuel Ethanol Production from Food Waste in Consideration of By-Product Utilization

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Abstract: In this paper, a life cycle assessment was used to evaluate fuel ethanol production from food waste with a capacity of 20 tons/day. The energy and pollution emissions during the whole process were recorded and compared by the method of electricity conversion to standard coal. Different indicators, such as GWP (global warming potential), ODP (ozone depletion potential), AP (acid potential), EP (possibility of eutrophication), POCP (photochemical oxidation potential), and DUST (dust), were used to perform an environmental impact analysis with and without by-product utilization. The result shows that the indicator sequence under the weighted factor sequence was AP > DUST > GWP > ODP > EP > POCP. The consideration of by-products decreased the values of GWP, AP, and DUST significantly; EP declined slightly; ODP and POCP increased; and the overall energy output was negative. The consideration of by-product utilization was determined to be environmentally friendly.

Keywords: environmental implications; food waste; life cycle assessment; ethanol; by-product

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1. Introduction

Food waste has the characteristics of a large quantity, high moisture content, ease of decay, and high oil content [1,2]. It negatively affects the environment without proper treatment; however, food waste is a nutrition-rich resource. The recycling technology mainly lies in feed, fertilizer production, anaerobic lactic acid production, methane, hydrogen, and so on [3–5]. Ethanol production from food waste is an effective method to accomplish its recycling [6]. Since 2020, garbage sorting has been carried out in China, and the percentage of food waste in municipal solid waste increased greatly; in Beijing City, for example, more than 6000 tons of food waste was produced. The proper treatment of food waste and evaluations of the economic and environmental assessments of the treatment are very important.

A life cycle assessment is an effective environmental management tool for dealing with the complex interaction between the environment and a product or process [7]. It is widely used in the fields of mechanical and electrical products, fuel systems, and agricultural systems, providing the methods and the basis for the evaluation of the green design of products and technological processes [8].

Based on life cycle assessment models, there are some studies on food waste composting, landfilling, and grain-based-ethanol and waste-to-ethanol production processes. Du Xin [9] used a life cycle assessment to compare the two recovery processes—composting and thermal hydrolysis. The results showed that the two processes were different in terms of global warming, ecotoxicity, acidification, and eutrophication. The total environmental impacts of thermal hydrolysis were 62.5% of composting as a result of having less effects on the three categories of acidification, eutrophication, and global warming. Thermal hydrolysis was found to be an effective regeneration process with less environmental impacts.

Mi-Hyung Kim and Jung-Wk Kim [10] evaluated feed manufacturing (including dry feeding and wet feeding), composting, and landfilling as food waste disposal options from the perspectives of global warming and resource recovery. Feed manufacturing and composting, the common treatment methods currently employed, have been known to be environmentally friendly. However, this study showed that they could negatively affect the environment if their by-products were not appropriately utilized as intended.

Hsien H. Khoo [11] investigated the environmental performance of four food waste conversion scenarios based on a life cycle assessment perspective, considering air emissions, useful energy from incinerators, and the anaerobic digestion (AD) process, as well as carbon dioxide mitigation from compost products derived from the dig estate material and a proposed aerobic composting system. The total normalized results showed that the proposed small-scale aerobic composting system was more environmentally favorable than incinerators but less ideal than the AD process. By making full use of the AD's Recycling Phase II process alone, the Singapore Green Plan 2012 aimed to increase the recycling of food waste to 30%, which could easily be achieved, as well as reduce global warming impacts.

A life cycle assessment was carried out for the whole process of sugarcane production and processing in Australia [12]. Sugarcane gains some comparative advantages through its high monosaccharide yield. There is also the start-to-cradle life cycle assessment that was used as a decision management tool for offshore seaweed cultivation, where 100 years of plantation data were analyzed for ethanol biofuel production [13]. It was confirmed that one ton of seaweed is equivalent to a net reduction of 0.13 tons of atmospheric CO_2 through this sustainable management model. A life cycle assessment was used to determine the environmental impact of cellulase recovery from coffee shells throughout the process [14]. This is the first LCA study to be applied to a complete solid-state fermentation process, including the downstream phase, on a representative scale. Overall, the findings indicated that improvements in downstream processes will help to reduce environmental impacts and costs.

Besides traditional substrates, some new materials such as microalgae were chosen to conduct a life cycle assessment to evaluate the environmental impact of microalgal oil produced by two kinds of microalgae, *Chlorella* sp. and *Schizochytrium* sp., and the research pointed out that glucose consumption is one of the main factors causing environmental impacts [15]. A variety of alternative carbon sources, including cassava starch (CS), honey (MO), sorghum juice (SJ), and sugarcane juice (SCJ) derived from non-food crops, can be used to replace glucose in algal oil production. These alternative carbon sources are either industrial waste or more productive than corn. By replacing glucose with alternative sugars (MO, SJ, and SCJ), all environmental impacts were reduced; in particular, eutrophication and non-carcinogens were reduced by more than 50% [16]. The use of a life cycle assessment described the adverse effects of electricity consumption (92.84%) and ammonium sulfate use (6.17%). Still, using renewable energy and reducing salt consumption could help to reduce these impacts. A life cycle assessment of fuel ethanol from biomass resources showed that the global warming potential (GWP100a) of 1 kg of ethanol produced via direct and indirect fermentation routes was 0.729 kg CO_2 eq/kg ethanol and 0.718 CO_2 eq/kg alcohol, respectively [17]. The results showed that fuel ethanol produced via indirect bio fermentation was more feasible economically, more friendly to the environment, and attractive to the capital market.

The paper also presented the importance of high-value-added by-product utilization. These high-value-added by-products are often oxygen-containing compounds that are not easily produced by petrochemical processes, greatly improving the economic viability of the process and potentially reducing the total environmental impact of the entire process. At the present stage, most LCA studies focus on the analysis of the fermentation process, and there is little analysis of the comprehensive utilization of by-products.

Sven Lundie and Gregory M. Peters [18] evaluated an environmental assessment of alternative means of managing food waste based on the life cycle assessment methodology.

They covered the service provided by a household in-sink food waste processor (FWP) unit, and three alternatives that were considered were home composting, landfilling food waste with municipal waste ("codisposal"), and the centralized composting of green (food and garden) waste. Jacqueline Ebner et al. [19] analyzed the life cycle GHG emissions associated with a novel process for the conversion of food processing waste into ethanol (EtOH) and the co-products of compost and animal feed. The process produced 295 L ethanol/ton of dry feedstock. The lifecycle GHG emissions associated with the ethanol production process were 1458 gCO_2/L ethanol. When the impact of avoided landfill emissions from diverting food waste to use as feedstock was considered, the process resulted in net-negative GHG emissions and an approximately 500% improvement relative to corn ethanol or gasoline production. This finding shows how feedstock and alternative waste disposal options have important implications for life cycle GHG results for waste-to-energy pathways.

In this study, a life cycle assessment was used to investigate the whole process of ethanol production from food waste, and an analysis of the environmental impact assessment of the entire process was made. An energy consumption calculation and six factors, which were classified as GWP, ODP, AP, EP, POCP, and DUST, were included in this study. By-products and their utilization process were also considered in this study.

2. Materials and Methods

2.1. Goal and Scope Definition of LCA of Ethanol Fermentation from Food Waste

The food waste ethanol fermentation process is shown in Figure 1. Food waste was transported to disposal sites, and after going through the pretreatment unit, oil and other parts were collected. The separated oil was used for biodiesel production, and the other parts were mixed with a certain amount water to a ratio of 2:1 (100 g food waste with 50 g water) to achieve the proper substrate moisture. Then, glucoamylase (100 u/g food waste) was added for saccharification, followed by yeast fermentation, and carbon dioxide was emitted. After fermentation, the fermentation broth was centrifuged for 5 min at 4000 r/min. Then, solid residues were used as refuse-derived fuels (RDFs), and the liquid parts underwent sewage treatment and were then discharged.

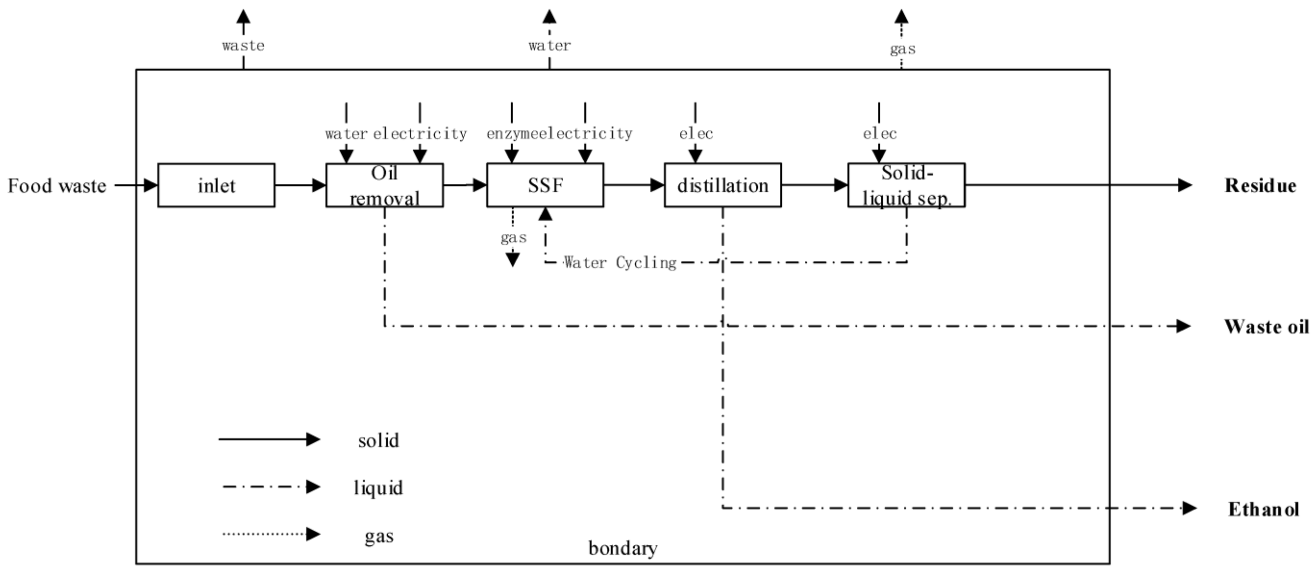

Figure 1. The boundary of ethanol fermentation from food waste.

The impact of ethanol fermentation from food waste needs to be clarified, and the significance of by-product resource utilization in the whole process was also studied. The life cycle assessment method was adopted to examine the energy demand and pollutant emissions of each link to determine the impact of the entire process on the environment. The significant influencing factors were identified, and improvement measures were proposed.

2.2. Inventory Analysis of the Process

The LCA inventory for each unit was recorded for resources, energy, and the corresponding emissions. The material balance for ethanol fermentation from food waste and by-product utilization are shown in Figure 2. The pilot process's daily processing capacity was determined to be 20 tons in total. Food waste was firstly fed to the sorting areas, and complex substances were recycled for metals, plastics, and other recyclable materials. The oil in the food waste was determined to be about 8%; then, 1.5 t of waste oil was recovered and collected in oil resource tanks. This oil was transported to a company for biodiesel production. The parameters for ethanol fermentation from food waste were taken from a pilot-scale project operated in Beijing. This pilot-scale project is run by a company, and electricity was used as the main energy source. The operation parameters were obtained from the company, and those that were not easily recorded on site were obtained in the laboratory and from the literature. Some power data were used from the Statistical Yearbook of China's electricity consumption data, and the corresponding environmental emissions per kilowatt of electricity are shown in Table 1.

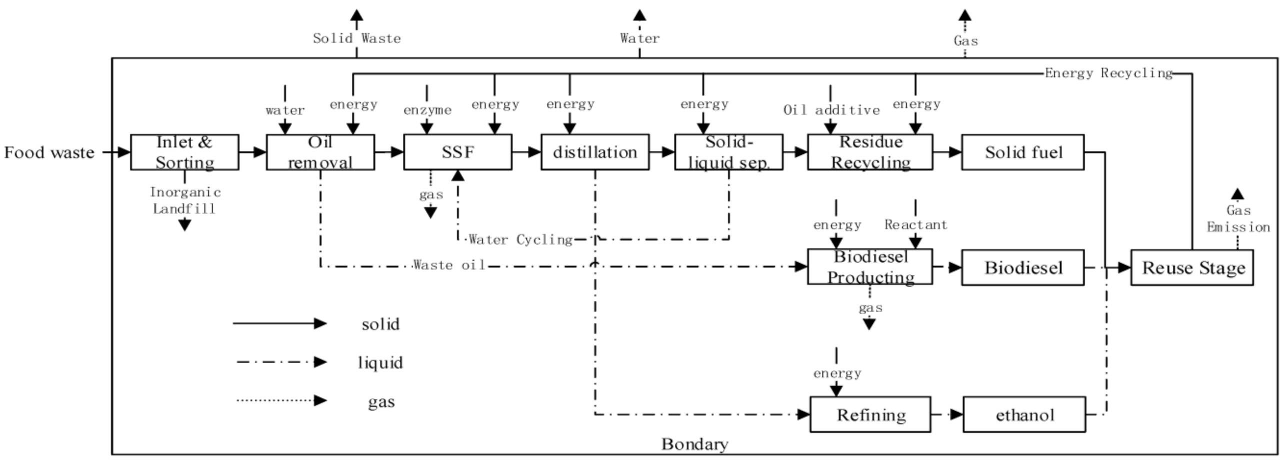

Figure 2. The boundary of ethanol fermentation from food waste.

Table 1. Environment emissions per kWh.

Emission	N_2O	SO_2	CO	No_x	CO_2	HC	Dust	COD	SS
Quantity kg/kwh	1.00×10^{-4}	1.16×10^{-2}	1.30×10^{-4}	5.14×10^{-3}	1.25×10^{0}	1.10×10^{-4}	6.14×10^{-3}	3.10×10^{-4}	3.20×10^{-4}

In this study, the used energy source was electricity from coal power. Moreover, the corresponding emission pollution was obtained from statistical data; that is to say, the electricity used was converted to the coal consumed in the power station, and the corresponding pollution emission obtained from the yearly book was used for calculations during the process evaluation.

The data were collected by the power input according to Table 1. Based on the pilot project and lab data, the pollutants released into the air, water, and soil from the food waste ethanol fermentation process are recorded in Table 2. The discharge of water pollutants mainly came from the separation process.

Table 2. List of LCI.

Emissions Pathways	Pollutants	Emissions (kg/t)
Atmosphere	N_2O	6.58×10^{-2}
	SO_2	7.63×10^{0}
	CO	8.55×10^{-2}
	NOx	3.38×10^{0}
	CH_4	2.78×10^{0}
	CO_2	8.67×10^{2}
	HC	7.23×10^{-2}
	Dust	4.04×10^{0}
Water body	COD	2.04×10^{-1}
	SS	2.10×10^{-1}
Soil	Solid waste	1.20×10^{2}

3. Results and Discussion

This study utilized food waste as a raw material for ethanol fermentation. To understand food waste utilization in the current stage is of great importance. Research has developed systems for "smart food waste recycling bins" (S-FRBs) and used a life cycle assessment to determine the environmental impacts associated with S-FRB technology to facilitate the conversion of food waste into end-products suitable for use as energy in line with circular economy principles [20]. Studies of these different scenarios suggest that further reductions in CO_2-equivalent emissions are possible during food waste disposal. The feasibility of adopting S-FRB technology in Hong Kong is highlighted in terms of environmental impact.

Another concern is the raw materials used for ethanol production; the majority of the substrates currently used are food crops. Thus, research in such a field would be useful for our study using food waste as a feedstock. The selection of crops with optimal environmental performance is equally important in the production of bioethanol [21]. Studies have investigated straw as agricultural waste, Napier grass as an energy crop, and short-rotation eucalyptus as a feedstock for bioethanol. In addition, the LCA of two on-site programs also investigated the utilization of fermented wastes (pellet fuel and molded pulp feedstock). In Taiwan, the field production of molded pulp products using fermented waste is 5% and 49% higher, respectively, than that of recycled newspaper and untreated chemical pulp. A fermentation waste utilization plan can therefore provide a broader assessment for planning the use of alternative crops for bioethanol production. The energy conversion characteristics and environmental impacts of the biomethane produced by both microalgae and food waste phases using a life-cycle approach were comprehensively assessed, and the contribution of the system process and its improvement potential were identified [22]. The final net energy ratio of the whole system was 0.24. At the present stage, analyses of kitchen waste resource utilization are mostly carried out on the process and final product, so it is necessary to strengthen the comprehensive utilization and analysis of by-products.

3.1. Life Cycle Assessment of Ethanol Fermentation

Standardized reference values and weight categories were calculated according to the data in Tables 2 and 3, respectively. The corresponding pollutant emission inventories were evaluated using the six imputations. The purpose of this study was to determine the GWP (global warming potential), ODP (ozone depletion potential), AP (acid potential), EP (eutrophication possibility), POCP (photochemical oxidation potential), and DUST (dust). The characterization, standardization, and empowerment results for the life cycle assessment are shown in Table 4.

Table 3. Environmental impact classification, characterized equivalent factor, normalized reference value, and weight factor.

Environmental Impact Categories	Contamination Factor	Characterized Equivalent	Standardized Reference Value kg.eq./Capita.yr	Weighting Factor
GWP	CO_2	1.00×10^{0}	3.59×10^{3}	0.74
	CH_4	2.10×10^{1}		
	HC	1.70×10^{3}		
	N_2O	2.96×10^{2}		
ODP	HC	3.40×10^{-2}	1.03×10^{-1}	3.74
AP	SO_2	1.00×10^{0}	4.19×10^{1}	1.32
	NOx	7.00×10^{-1}		
EP	COD	2.20×10^{-1}	8.35×10^{0}	1.28
	NOx	1.35×10^{-1}		
POCP	CO	2.70×10^{-2}	6.05×10^{0}	1.18
	CH_4	6.00×10^{-3}		
DUST	Solid contaminants	Actual emissions	2.90×10^{1}	1.77

Table 4. Environmental impacts of ethanol fermentation from food waste.

LCA Result	GWP	ODP	AP	EP	POCP	DUST
Characterization results	1.07×10^{3}	2.46×10^{-3}	9.99×10^{0}	5.01×10^{-1}	1.90×10^{-2}	4.04×10^{0}
Standardization results	2.98×10^{-1}	2.39×10^{-2}	2.38×10^{-1}	6.00×10^{-2}	3.14×10^{-3}	1.39×10^{-1}
Empowering results	2.20×10^{-1}	8.93×10^{-2}	3.15×10^{-1}	7.68×10^{-2}	3.71×10^{-3}	2.46×10^{-1}

The evaluation results for the LCA of ethanol fermentation from food waste were as follows: the impact of GWP was 1.07×10^{3} kg CO_2 eq/kg, ODP was 2.46×10^{-3} kg CFC − 11 eq/kg, AP was 9.99×10^{0} kg SO_2 eq/kg, EP was 5.01×10^{-1} kg PO_4^{3-} eq/kg, PO was 1.90×10^{-2} kg C_2H_4 eq/kg, and DUST was 4.04×10^{0} kg.

Figure 3 shows the results of the environmental impact of the food waste ethanol fermentation process. In addition to the potential impact of global warming after the empowering value decreased, the other effects of the latent values increased. The environmental impact of the potential values of the indicators followed the sequence of GWP > AP > DUST > EP > ODP > POCP. The potential impact of global warming was the most significant factor of the six. Since the analysis came from the coal power electricity conversion methods, we could see that the amount of dust was even higher in this study; in fact, this is one of the shortcomings of this study. Since a real plant generally uses natural gas as the power source, the result will be different. However, in the project operated in the city, such a result also contains useful information.

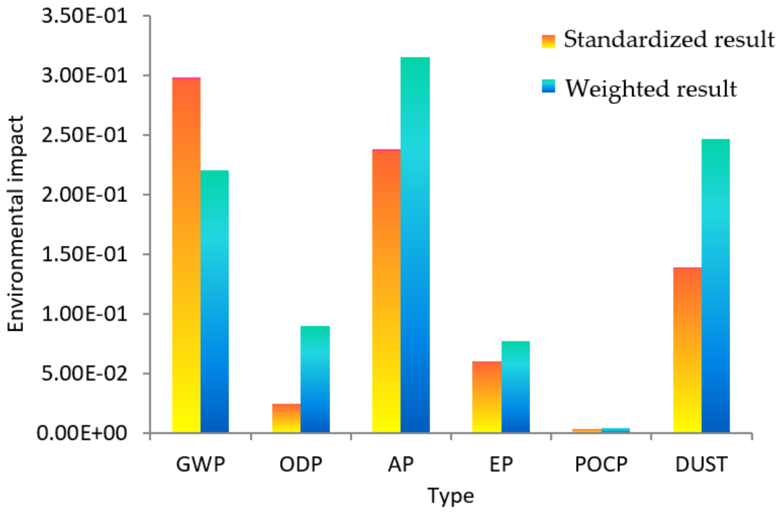

Figure 3. Total environment impact of ethanol fermentation from food waste.

3.2. The Consideration of By-Product Utilization

To fully examine the environmental impact of the food waste ethanol fermentation process, the utilization of by-products was considered. Firstly, the environmental impact of biodiesel production from the waste oil in this process is shown in Table 5. The data mainly came from the literature. Traditional methods use alkaline as the catalysts. Oil is firstly hydrolyzed to produce fatty acids and glycerol, the produced fatty acids react with methanol to produce biodiesel, and this is used as a kind of fuel just like gasoline.

Table 5. The environmental emissions of biodiesel production and utilization.

Production Process (kg)	CO_2	SO_2	NOx	Dust	HC	CO	Energy (Tce)
Biodiesel Preparation	2.61×10^{-2}	4.31×10^{-4}	2.16×10^{-5}	2.16×10^{-4}	0	0	1.34×10^{0}
Use Emissions	2.597	0	5.62×10^{-2}	0	4.20×10^{-3}	7.48×10^{-3}	0

Moreover, the biofuel production from fermentation residues was calculated in the process. The amount of solid fuel produced in the process was calculated based on an industrial analysis and an elemental analysis. The proportion of total combustible solid fuel was 78.8%, and the post-combustion ash was 21.2%, calculated according to Table 6.

Table 6. The environmental emissions from combustion process for per ton of RDF.

Type	G_{sd}	G_{SO2}	G_{CO}	G_{NOX}	G_{CO2}	Ash
Quantity (kg)	6.17×10^{0}	9.92×10^{0}	4.85×10^{1}	1.38×10^{1}	1.84×10^{3}	2.12×10^{2}

The biodiesel and RDF produced in this study would be used for the energy needed in the process. Since the ethanol production process is an energy consumption process, particularly the distillation process, the use of by-products for energy would make the process environmentally friendly. Since the utilization of by-products generated energy equivalent to the power input of the original process, the surplus energy was negative. In order to investigate the input and output of the energy flow of the whole process, the products after by-product utilization were converted into energy for calculation. The calorific value of standard coal was 29.31 MJ/kg, the gross calorific value of fuel ethanol was 29.66 MJ/kg, and the calorific value of biodiesel was 40.20 MJ/kg (9600 kcal/kg, 1.341 kg of standard coal is consumed for the preparation of each kg of biodiesel). The calorific value of the biomass fuel was added according to the percentage of the two materials in the optimal ratio, and its calorific value was about 24.09 MJ/kg. The whole energy input and output were calculated in the process, and the result shows that the net energy was negative, which indicates that, with the proper use of the by-products, the system could realize energy self-sufficiency. The total emission inventory for the process is shown in Table 7.

Table 7. The list of LCI with by-product utilization.

Emission	Pollutants	Quantity (kg/t)
Air	N_2O	-1.25×10^{-1}
	SO_2	-1.12×10^{1}
	CO	1.64×10^{1}
	NOx	2.34×10^{0}
	CH_4	-5.29×10^{0}
	CO_2	-6.83×10^{2}
	HC	1.77×10^{-1}
	Dust	-5.63×10^{0}
Water	COD	-3.88×10^{-1}
	SS	-4.00×10^{-1}
Soil	Solid-Waste	-1.58×10^{2}

From Table 8, the environmental effect data were acquired, and the impact categories for the reference value and the weight value were calculated in consideration of by-product utilization.

Table 8. Environmental impacts of food waste ethanol fermentation with by-product utilization.

LCA Result	GWP	ODP	AP	EP	POCP	DUST
Characterization	-5.30×10^{2}	6.03×10^{-3}	-9.57×10^{0}	2.31×10^{-1}	4.11×10^{-1}	-5.63×10^{0}
Standardized	-1.48×10^{-1}	5.86×10^{-2}	-2.28×10^{-1}	2.76×10^{-2}	6.80×10^{-2}	-1.94×10^{-1}
Weighted result	-1.09×10^{-1}	2.19×10^{-1}	-3.01×10^{-1}	3.53×10^{-2}	8.02×10^{-2}	-3.44×10^{-1}

The results of the standardized value of the life cycle assessment are shown in Figure 4. By-product utilization resulted in the energy and pollutant emissions being within the boundaries of the life cycle assessment. The figure shows that GWP, AP, and DUST dropped significantly. After the by-product utilization, a negative impact was observed to eliminate the environmental impact of the potential value. This was because the entire process was a net-positive energy output, the offset energy output of electrical energy consumption, so the overall process of CO_2, SO_2, CH_4, soot, and solid waste emissions dropped, and these became negative emissions. EP decreased slightly, and this was due to the utilization of by-products decreasing the usage of energy from electricity; thus, the NOx emissions reduced. When it came to the sewage treatment, since the ethanol liquid was carried in a circular manner in the process, the COD emissions decreased compared with before. However, for the biodiesel and solid fuel produced in this process, although they saved energy usage, these two products were burned during their utilization; thus, the NOx emissions increased. Even though part of the power could be offset to reduce the nitrogen oxide emissions, the total emissions of nitrogen oxides decreased a little, and, finally, the eutrophication impact value decreased a lot. ODP and POCP increased. The amount of photochemical oxidation by-products increased due to the by-product utilization, and although the process of CH_4 emissions from electricity generation decreased, the emissions of fermentation residues produced by the solid fuel resulted in the emissions of CO due to incomplete combustion. If a higher-combustion-efficiency furnace was adopted, combustion would be conducive to the whole process. The potential impact of ozone depletion was due to the increased emissions of HC, which was caused by the biodiesel production process.

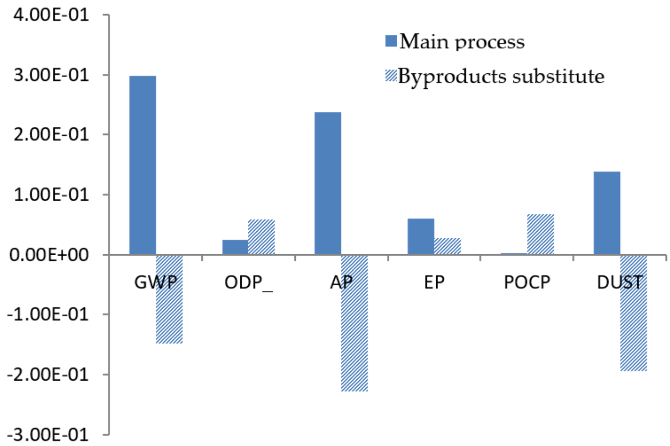

Figure 4. Environmental impact according to normalized results between the main fermentation process and by-product utilization.

The environmental impact index for ethanol fermentation from food waste with the utilization of by-products was negative, and the whole process was environmentally friendly and helped to eliminate some of the effects of the latent value. Thus, the proper use of by-products plays an important positive role in affecting the entire system environment.

Meng et al. simulated the process of converting municipal solid waste to butanol and ethanol and performed a life cycle evaluation [23]. The results showed a net primary energy demand of −559.69 MJ/ton of municipal solid waste (butanol and ethanol). At the same time, the net GHG emissions were −6.32 kg CO_2 eq/ton of municipal solid waste, achieving a 115% GHG reduction compared to gasoline. In addition, their study showed that electricity by-products from fermentation solid residues had a higher energy efficiency because more biomass was not converted to fuel during the fermentation process. Together with the heat from the remaining solid residue, the total energy yield could be increased from 28% to 37%, and the greenhouse gases could be further reduced by 40%. This suggests that the production of biofuels from food waste and their use as an alternative to fossil fuels can lead to greenhouse gas emission reductions and that the production of by-products from fermentation solid residues is also significant, with a large amount of biomass not converted to fuel being included. The corresponding result was also discovered in our study.

Life cycle greenhouse gas (GHG) impacts for the conversion of food waste into ethanol and by-products were investigated by Ebner et al. In their research, food waste was used for fermentation to produce ethanol, and compost and feed were obtained as by-products. The life cycle GHG emissions associated with the ethanol production process were 1458 gCO_2 e/L EtOH. In contrast, the avoided emissions from by-product composting and animal feed were only 54 gCO_2 e/L EtOH and 260 gCO_2 e/L EtOH. This showed that by-product utilization during ethanol fermentation is particularly important. In this study, the production of ethanol distillation solid residue as a biomass fuel was a more sensible choice from the point of view of reducing life cycle greenhouse gas (GHG) impacts.

Brancoli et al. compared the environmental impacts of the ethanol production, feed, and beer utilization pathways of overproduced bread. The results showed that all three processes can achieve avoided greenhouse gas emissions [24]. The ethanol production pathway had optimal results, achieving a net savings of −0.56 kg CO_2 eq per kg of bread as ethanol. The pathways for feed and beer production were −0.53 kg CO_2 eq per kg of bread and −0.46 kg CO_2 eq per kg of bread, respectively. This corresponds to our results showing that the production of ethanol from food waste had the advantage of an excellent reduction in the environmental impact of the treatment process.

The global energy supply problem is imminent, with a severe shortage of fossil fuels in various countries and the transport sector of the European Union (EU) being completely dependent on imported fossil fuels. Replacing gasoline with liquid fuels produced from renewable resources is a high-priority goal for many countries around the world. Ethanol, as a highly promising biofuel, is a good choice for replacing fossil fuels. With its high specific calorific value, the combustion process does not produce toxic gases, and it also reduces the impact of the greenhouse effect caused by the burning of fossil fuels. Our research provides new ideas for the management of global energy systems, and the production of bioethanol from food waste is a viable operation that will alleviate global energy supply problems. The life cycle assessment of fuel ethanol production from food waste and by-product utilization provided useful information for food waste management from the perspective of reducing environmental impacts. The findings may be useful for comparing and analyzing the different treatment technologies for food waste to choose the most appropriate methods.

4. Conclusions

(1) LCA was used for ethanol fermentation from food waste, and the characterization results show that the sequence was GWP > AP > DUST > EP > ODP > POCP. An energy analysis of ethanol fermentation from food waste demonstrated that the net energy output for the whole process was negative, and the whole process could realize energy self-sufficiency.

(2) The utilization of by-products in the process achieved a better effect. The GWP, AP, and DUST latent values dropped significantly, the EP value showed a slight decline, and ODP and POCP increased. The whole process was proved to be environmentally friendly and could eliminate some bad effects. The rational use of by-products plays an important positive role in environmental protection and resource utilization.

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