Heliyon 8 (2022) e10975

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Chula model for sustainable municipal solid waste management in university canteens

Palaporn Sukma [a], Kanokpish Srinok [a], Seksan Papong [d], Nuta Supakata [a,b,c,*]

[a] Department of Environmental Science, Faculty of Science, Chulalongkorn University, Bangkok 10330, Thailand
[b] Research Group (STAR): Waste Utilization and Ecological Risk Assessment, The Ratchadaphiseksomphot Endowment Fund, Chulalongkorn University, Thailand
[c] Chula Zero Waste Project, Chulalongkorn University, Bangkok 10330, Thailand
[d] Technology and Informatics Institute for Sustainability, National Science and Technology Development Agency, Pathum Thani 12120, Thailand

ARTICLE INFO

Keywords:
University canteens
Sustainable MSW management
Life cycle assessment
Chulalongkorn University

ABSTRACT

Managing the large amount and variety of waste produced by university canteens is challenging. This study used life cycle assessment (LCA) to investigate sustainable municipal solid waste (MSW) management solutions for Chulalongkorn University (CU) canteens. This study assessed three scenarios for MSW management in CU canteens: the past scenario (prior to the Chula Zero Waste Project in 2016; S1); the current scenario (2017–2021, when the Chula Zero Waste Project's MSW management system was used; S2); and the future scenario (after 2021 with the new MSW management option for CU canteens under Chula Zero Waste; S3). The obtained results were characterized by eight impact categories: climate change, ozone depletion, terrestrial acidification, freshwater eutrophication, human toxicity, photochemical oxidant formation, particulate matter formation, and fossil depletion. The LCA results show that the future scenario (S3) under the Chula Zero Waste Project is sustainable for MSW management. The most environmentally sustainable MSW plan for CU canteens is to reduce, separate it at the source, and reuse materials instead of landfilling mixed waste.

1. Introduction

Municipal solid waste (MSW) consists of a highly heterogeneous mixture of residential, commercial, industrial, institutional, and other waste materials (Rafizul and Alamgir, 2012). Approximately 2.1 billion tons of MSW are generated globally each year and are predicted to reach 3.4 billion tons by 2050 (Kaza et al., 2018). In Thailand, MSW amounted to 27.8 million tons in 2020; it tends to increase every year, particularly in Bangkok, where about 10,500 tons per day are generated (Simachaya, 2020). Consequently, the Twelfth Thai National Economic and Social Development Plan (2017–2021), based on the sustainable development goals (SDGs), focuses on MSW and hazardous waste management (Office of the National Economic and Social Development Board, 2016). The plan lays out 10 national strategies, one of which is for growth that is good for the environment and aims to manage and utilize at least 75% of MSW.

In 2017, Chulalongkorn University (CU) established its first sustainable university policy based on King Rama IX's sufficiency economics philosophy and the United Nations Sustainable Development Goals to become a university of academic excellence that promotes social, economic, and environmental sustainability. The objective of the university is to promote sustainable practices, including environmental and resource management. CU launched the Chula Zero Waste Project (2017–2021) in a bid to ensure sustainable waste management; a collaboration with the Environmental Research Institute and the Office of Physical Resource Management (Chulalongkorn University, 2020). CU adopted six plans on waste database management, waste reduction, waste separation at sources, waste collection systems, organic waste management, and information tools/media on sustainable waste management. The implementation of this project involved the overall waste management of university office buildings, common areas, and canteens. MSW Management in CU Canteens (a sub-project under the Chula Zero Waste Project) aims to reduce MSW and encourage CU students and staff to separate waste at the source in CU canteens.

To achieve appropriate and sustainable MSW management, life cycle assessment (LCA) was used to assess the environmental impact of MSW management in CU canteens. LCA is a scientific method for comparing and evaluating the environmental impact of products and services, as well as solid waste systems (Giugliano et al., 2011; Allesch and Brunner, 2014), by identifying and assessing total amount of resources consumed

---

* Corresponding author.
E-mail address: nuta.s@chula.ac.th (N. Supakata).

https://doi.org/10.1016/j.heliyon.2022.e10975
Received 28 September 2021; Received in revised form 5 October 2021; Accepted 30 September 2022

as well as all emissions and wastes released into the environment (Clift, 2006, 2013). This allows policymakers to compare technologies, scenarios, and processes and evaluate their environmental performance (Finnveden et al., 2005).

LCA has been used to compare alternative scenarios in MSW management. For example, Yay (2015) used LCA to determine the environmental aspects of a less impactful MSW management system in Sakarya, Turkey. The findings showed that landfilling and incineration are the worst solutions for the final disposal of waste, whereas composting and material recovery are comparatively better alternatives. In terms of enhanced sustainability, an integrated system is considered the solution to the existing waste management challenge. The researchers recommend that waste recycling activities be improved by separating waste at the source and that the public be educated on the significance of recycling. Similarly, Liu et al. (2017) used LCA to compare four garbage treatment systems in Beijing—separate collection and transportation, sanitary landfill systems, fluidized bed incineration systems, and composting systems. They reported that the separation rate and the sorting of waste were crucial to the increased yield of recycled materials.

Coelho and Lange (2018) investigated sustainable waste management solutions for the Brazilian city of Rio de Janeiro by utilizing LCA as a technique for comparing different waste management systems and selecting the solution with the least environmental impact. According to the research, a scenario with a high rate of collection and recycling delivers the best performance with the least impact on the environment. Furthermore, scenarios emphasizing material recovery produced greater environmental benefits than alternatives emphasizing energy generation. Wang et al. (2020) used LCA to determine the historical GWP for MSW management in Nottingham. During the study period, the results showed a continuous reduction in greenhouse gas (GHG) emissions associated with MSW management, and this reduction can be attributed to improvements in waste collection, treatment, material recycling, and waste prevention. Separating food waste from incinerated waste, treating organic waste with anaerobic digestion, and pretreating incinerated waste in a material recovery facility might all result in a net reduction in GHG emissions. To achieve the prospective scenario, it is necessary to boost public participation and focus on the quality of recycled and recovered materials.

Other authors have emphasized the LCA methodology for food waste management (Brancoli et al., 2017; Zorpas et al., 2018). Their results demonstrated that separation of food waste at source can contribute to a net reduction of GHG emissions. There are studies on the management of food waste at school and university canteens. García-Herrero et al. (2019) investigated the environmental and financial impact of food consumption and waste in Italian public school canteens using a case study. In 2019, Zhang et al. (2021) quantified food waste to identify key influencing factors in Wuhan using direct weighing, questionnaires, statistical analysis, and a random forest model. LCA was also used to assess the environmental impacts of food waste. Besides focusing only on the management of food waste, few studies have addressed the environmental impacts of the entire MSW management system in university canteens. In this study, LCA was applied to choose the solution for MSW management in university canteens with the least environmental impact by comparing the three scenarios of MSW management in CU canteens: S1, which refers to the period before the Chula Zero Waste Project started in 2016 (past); S2, which was implemented from 2017 to 2021, where the MSW management system of the Chula Zero Waste Project has been in action (present); and S3, which provides CU canteens the option to choose the suggested MSW management option under the Chula Zero Waste Project after 2021 (future). Analysis was performed using SimaPro 8.3.0.0 and the ReCiPe Midpoint (H) V1.13/World Recipe H method. Climate change, ozone depletion, terrestrial acidification, freshwater eutrophication, human toxicity, photochemical oxidant formation, particulate matter formation, and fossil depletion are the eight effect categories discussed. The findings provide insights on how the Chula Zero Waste Project's MSW management practices contribute to the improvement of MSW management in CU canteens and support university policy and decision making for the future development of MSW management at CU. This information is beneficial for ensuring efficient management of waste and achieving sustainable development. This model can be applied to similar studies at different institutions and departments.

2. Materials and methods

2.1. Case study description

Chulalongkorn University, Thailand's first institution of higher learning, was founded in March 1917 in Bangkok, capital of Thailand. CU has 20 faculties, 23 colleges and research institutes, 8200 academic members and support staff, and 40,000 students, including undergraduate, postgraduate, and certificate program students (Chulalongkorn University, 2020), making it a significant source of MSW. MSW management in CU canteens is one of 16 sub-projects of the Chula Zero Waste Project launched in 2017 to reduce MSW and encourage CU students and employees to separate waste at 12 CU canteens. This initiative sampled 12 canteens in CU from 2016 to 2021 to quantify MSW. Chula Zero Waste Project employees corrected and monitored waste diaries kept by food vendors and cleaning staff.

Three scenarios of MSW management were evaluated in CU canteens: before the Chula Zero Waste system in 2016 (past); the Chula Zero Waste system from 2017 to 2021 (current); and a potential alternative beyond 2021 (future). MSW from 12 CU canteens were included in this study, including seven canteens under the physical resource management office, four canteens under faculty management, and the student dormitory unit. The sources of MSW in the CU canteens are consumers (students and staff) and food vendors.

2.1.1. Description of scenario 1 (S1)

S1 represents the MSW management system of CU canteens in 2016, before the Chula Zero Waste Project. The MSW in this scenario was managed by the CU office of physical resource management. The amount of waste generated by consumers and food vendors was approximately 851.27 tons/year. The waste composition by consumers consisted of food waste (55%), which was collected by farmers for feeding fish; plastic bottles (1%) were sold to recycling vendors; general waste (10%) and plastic cups (1%) were collected by the Bangkok Metropolitan Administration and disposed of in landfills. All the MSW of food vendors (33%) ended up in landfills without being separated. Overall, S1 MSW was used for fish feeding (55%), disposing of in landfills (44%), or recycling (1%). The waste streams of S1 are given in Figure 1.

2.1.2. Description of scenario 2 (S2)

S2 represents the waste management system carried out by the Chula Zero Waste Project from 2017 to 2021. In this scenario, plastic bags, foam packaging, and plastic cups were banned in CU canteens, and food vendors were encouraged to replace plastic cups with biodegradable paper cups known as "Chula zero-waste cups." Five types of bins were provided for consumers to separate waste at the source in canteens, including ice and water, Chula zero-waste cups, recyclables, general waste, and food waste. Two types of bins were provided for food vendors general and food waste bins.

Since the launch of the Chula Zero Waste Project, the amount of waste has been reduced from 851.27 tons/year to 617.42 tons/year. The composition of consumer waste included 235.91 tons/year (38.21%) of food waste was used as fish feed; 13.8 tons/year (2.24%) of plastic bottles were recycled; 11.79 tons/year (1.91%) of Chula zero-waste cups were used as plant grow bags and compost; and 43.02 tons/year (6.97%) of general waste was sent to landfills. Food vendors generate 146.4 tons/year (23.71%) of food waste, which was converted into compost, and 166.51 tons/year (26.97%) of general waste, which was sent to landfill. In general, 235.91 tons/year (38.21%) of MSW was used for fish feeding,

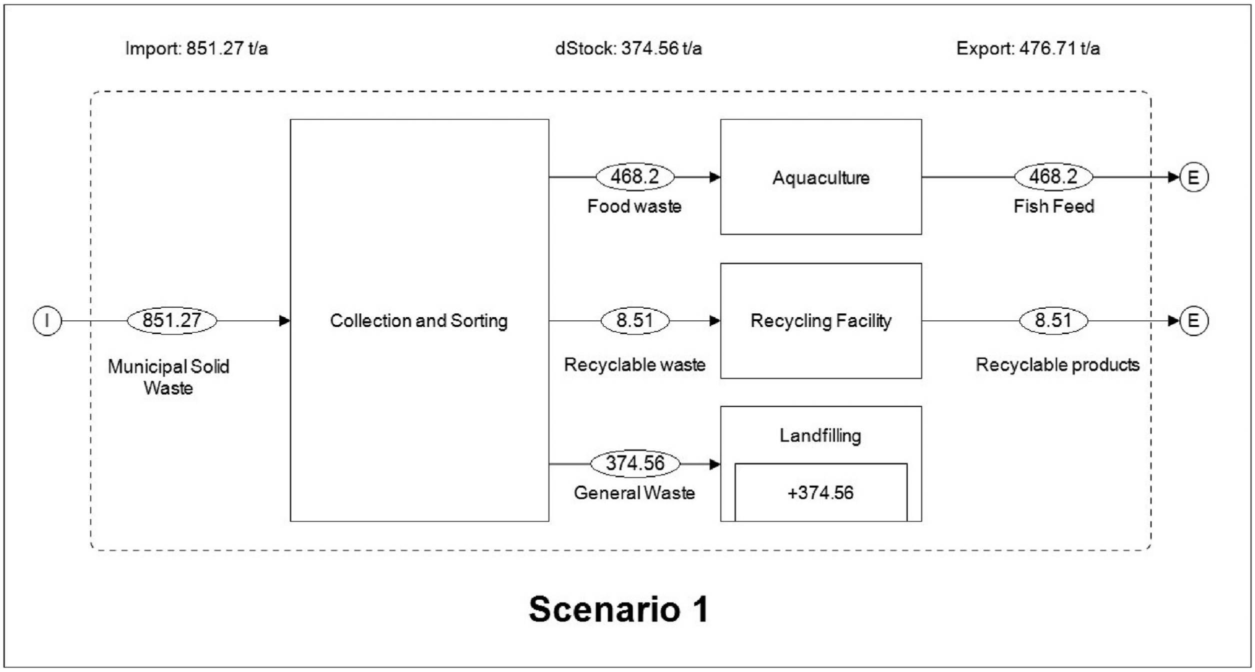

Figure 1. MSW flow of Scenario 1: Previous scenario before the Chula Zero Waste Project.

209.53 tons/year (33.94%) for landfill decomposition, 146.4 tons/year (23.71%) for composting, 13.8 tons/year (2.24%) for recycling, and 7.89 tons/year (1.29%) for plant grow bags. The waste streams of S2 are given in Figure 2.

2.1.3. Description of scenario 3 (S3)

S3 represents MSW management designed to achieve environmental sustainability with zero landfill waste. Refuse-derived fuel (RDF) would replace landfill because general waste in CU canteens, such as food wrappers and packaging, candy and snack bags, plastic bags, meatball skewer sticks, plastic cutlery/utensils, and napkins, have low-humidity and high-calorific value. This general waste will be converted into RDF and used as fuel with coal in a cement plant in Saraburi province. Five types of bins are provided for consumers to separate waste at the source in canteens; they are bins for ice and water, Chula zero-waste cups, recyclables (polyethylene terephthalate (PET) drink bottles), food waste, and RDF waste, known as “recycle plus”. Food vendors are provided with containers for recycling plus (RDF) and food waste. This study used the amount and composition of waste similar to S2. Generally, MSW management volumes in S3 were fish feed (38.21%), RDF (33.94%), compost

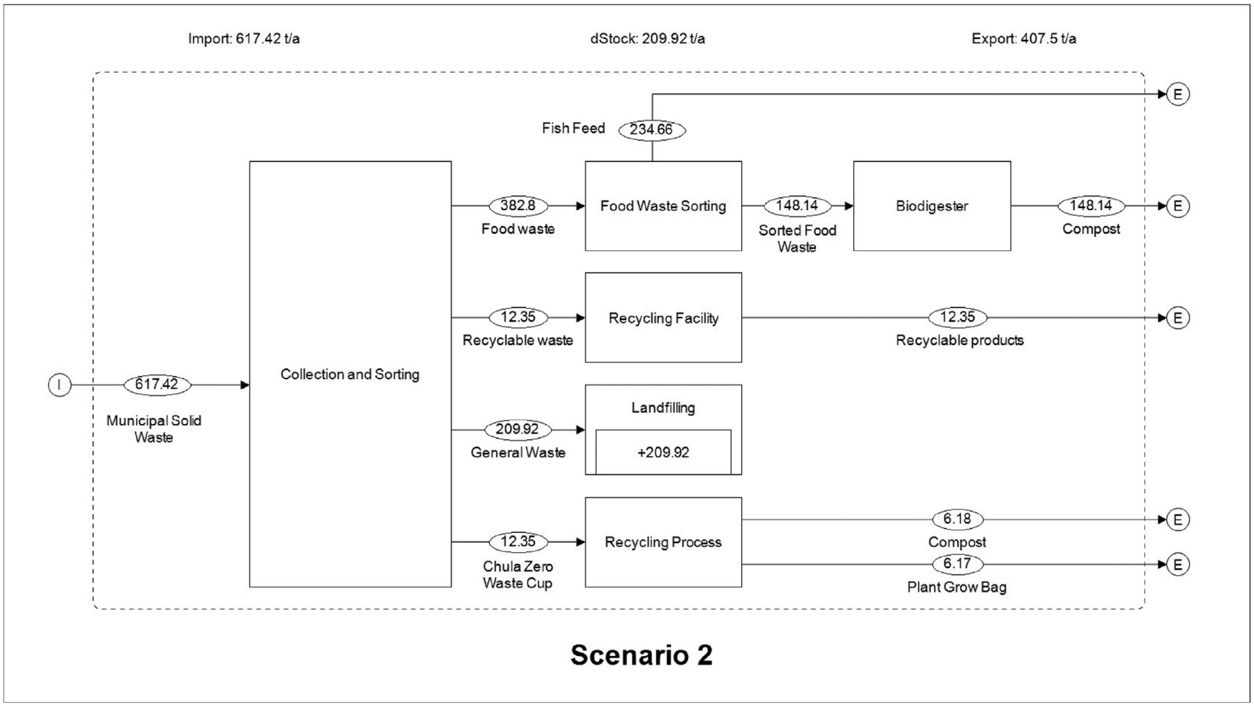

Figure 2. MSW flow of Scenario 2: Current scenario under the Chula Zero Waste Project.

(23.71%), recycling (2.24%), and plant grow bags (1.29%). The waste streams of S3 are given in Figure 3.

2.2. Life cycle environmental assessment

To achieve appropriate and sustainable MSW management in CU canteens, an environmental impact assessment method was performed using LCA (ISO, 2006a), a widely used decision support technique in waste management systems (Coelho and Lange, 2018). According to ISO (2006b), there are four basic steps in the assessment procedure in ISO 14040 and 14044 standards, and these four steps include (a) goal and scope definition; (b) life cycle inventory (LCI); (c) life cycle impact assessment (LCIA); and (d) life cycle interpretation.

(a) The objective was to compare scenarios in S1, S2, and S3 canteen MSW management. One ton of MSW generated in a CU canteen was defined as the functional unit. The assessment boundaries include collection, transport, treatment, and disposal of MSW generated in the canteen.
(b) Data for the LCI were collected from various primary and secondary sources, including reports, literature, and Ecoinvent databases in SimaPro software. The assumptions in this study include the following.

2.2.1. Fish feed

All food waste from CU canteens is used to feed fish. Farmers from fish farms near Bangkok travel 388 km to CU to collect food waste from CU canteens. A four-wheeled vehicle with a capacity of 3.2 tons is used for transportation.

2.2.2. Composting

It is assumed that the components of the Chula zero-waste cup are combined with rain tree leaves and branches and used as additives to improve soil quality. This process moves at 5.2 km/day. A truck that uses 6 km/L of fuel is used for transportation. Furthermore, the total amount of energy consumed during the composting process is 161.78 kW h per 12.94-tons cup. In this study, the composting process produced 4.18 tons of compost with about 3.4% nitrogen, 2.8% phosphorus, and 9.7% potassium.

2.2.3. Composting by biodigester

For anaerobic digestion, a biodigester is used to decompose food waste from the canteen. The transport distance in the anaerobic digestion process is 5.2 km/day. A 6-km/L diesel truck is used in transporting and composting process. This process produces approximately 70% bio-fermented water and 30% soil conditioners. This process uses 8400 kW h of electricity and 1440 kg of liquefied petroleum gas per 146-tons food waste. In this study, the soil conditioners are a by-product that contains about 3.6% nitrogen, 2.3% phosphorus, and 2.4% potassium.

2.2.4. Recycling

Recycling was considered in terms of transportation, compaction, and delivery to the recycling plant. The recycled waste from CU canteens included plastic bottles made of PET from bottles and polypropylene from labels. The two types of plastic are separated and transferred to a recycling plant to manufacture plastic granules. The vehicle used for transport is a four-wheeled vehicle with a capacity of 3.2 tons that travels a total distance of 66 km. Transportation from the recycling vendor to the recycling plant is by a six-wheeled truck that can carry 8 tons and a 10-wheeled truck that can carry 15 tons. The total distance from the recycling vendor to the recycling plant is 143 km. This study assumed that PET and PP wastes were mechanically recycled with a 70% efficiency (Cui and Sošić, 2019).

2.2.5. Landfill

Landfill was considered in terms of source transportation, compaction, and delivery to landfill. All waste that is separated from other types of waste and checked by the cleaning officer was assumed to be destined for landfill. A six-wheeled vehicle with a capacity of 5 tons transports waste from CU to the On Nut Garbage Disposal Plant in Bangkok, whereas a trailer with a capacity of 50 tons transports waste to a landfill site in Phanom Sarakham District, Chachoengsao Province. The net input of the landfill process per ton of MSW is 8.59 L of fuel, 3.52 kW h of

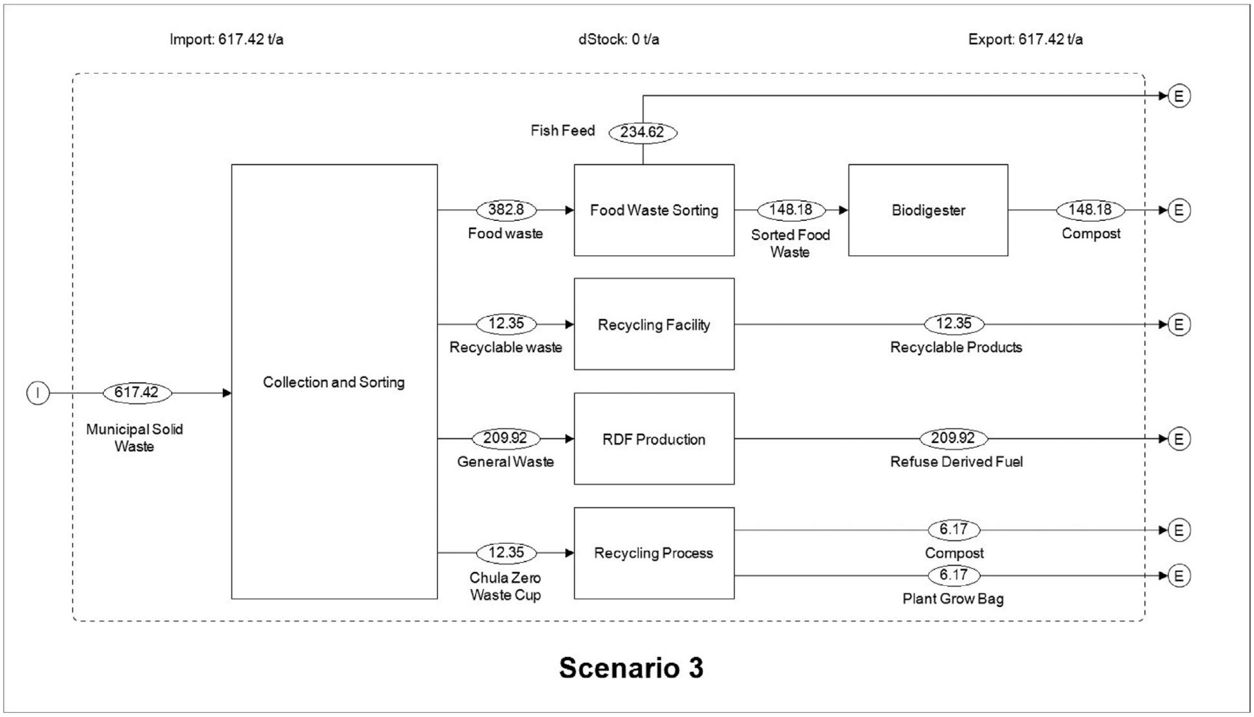

Figure 3. MSW flow of Scenario 3: Future scenario under the Chula Zero Waste Project.

electricity, 56.77 L of water, 1.65 kg of wire, and 1.11 kg of plastic. However, the outputs per ton of MSW are 86.69 L of wastewater, 0.07 kg of BOD, 0.12 kg of COD, 51.97 kg of methane, and 144.90 kg of biogenic carbon dioxide. The methane generated in this process was not collected for reuse.

2.2.6. Refuse derived fuel (RDF)

The general waste in S2 changed from landfill to the RDF in Scenario 3. The distance in the RDF process within CU is 5.2 km. A 6 L/km truck was used for transportation in this process. After waste collection, waste compaction process, which uses 586 kW h per 166-tons general waste. In addition, the distance from CU to the cement plant in Saraburi province is 163 km. This process uses a 10-wheeled truck that consumes 4 L/km of diesel. The RDF process uses 9481.57 kW h and 3408.93 kg of calcium hydroxide to produce 210 tons of RDF-5.

2.2.7. Plant grow bag

Chula zero-waste cups are used as nursery bags instead of bags made from low-density polyethylene (LDPE) because they biodegrade in 6 months. The zero-waste cups are transported 5.2 km. A 6-L/km truck of petrol was used to transport waste collected with food vendor waste from CU. This process eliminates 1676.35 kg of LDPE plastic bags.

(c) The LCIA consists of different elements such as classification, characterization, normalization, and weighting. Classification and characterization are mandatory elements according to ISO 14044. In this study, an LCIA of three scenarios of MSW management in CU canteens was performed using SimaPro 8.3.0.0 with the ReCiPe Midpoint (H) V1.13/World Recipe H method. Eight impact categories considered were climate change (kg CO_2 eq), ozone depletion (kg CFC-11 eq), terrestrial acidification (kg SO_2 eq), freshwater eutrophication (kg P eq), human toxicity (kg 1,4-BD eq), photochemical oxidant formation (NMVOC), particulate matter formation (kg PM10 eq), and fossil depletion (kg oil eq).

(d) An LCA comparison is used to decide the alternative resulting in the least environmental burden. This requires normalizing/transforming the absolute impact of each scenario into a relative impact. Normalization can help to choose the appropriate scenario for improving the product system (Heijungs et al., 2007). Normalization is done by dividing characterized results by an estimate of the total or per capita equivalent emissions in that impact category for a region (Eq. (1)). The ReCiPe midpoint H method has a world normalization reference, which compares results to estimations of annual world per capita emissions (Goedkoop et al., 2009). The eight impact category indicators were normalized and aggregated. The aggregation was performed by adding up all of the normalized impact category results (Coelho and Lange, 2018).

$$NI_i = CI_i/NR_i \tag{1}$$

where NI_i is the normalized impact per year of impact category i. CI_i is the characterized impact of impact category i. NR_i is the normalization reference for impact category i in a specific geographical region in physical units (per year).

3. Results

3.1. Environmental impacts of the three MSW management scenarios in the CU canteens

The normalized LCA results for each impact category were divided by disposal option for all scenarios. A negative value shows an environmental benefit/credit, whereas a positive value shows the presence of an environmental burden.

3.1.1. Past scenario (S1) before the Chula Zero Waste Project

The LCA results of S1 in Figure 4 show that food waste and general waste landfilling cause climate change. Food waste is the primary source of methane from landfills. The global warming potential of methane is 28 times higher than that of CO_2 (Singh et al., 2018). Ozone depletion from landfills had the smallest impact. Biodegradable waste (food waste) from landfills emits methane gas that depletes the ozone layer (Zangmo, 2017), as does fuel-intensive transportation (Borrion et al., 2012).

Landfilling causes most of the negative impacts of MSW management. Landfilling has a significant impact on climate change, fossil depletion, and photochemical oxidant formation. Using food waste for fish has the highest environmental impacts, especially on freshwater eutrophication. Freshwater eutrophication is caused by excess nutrients, including nitrogen (N)

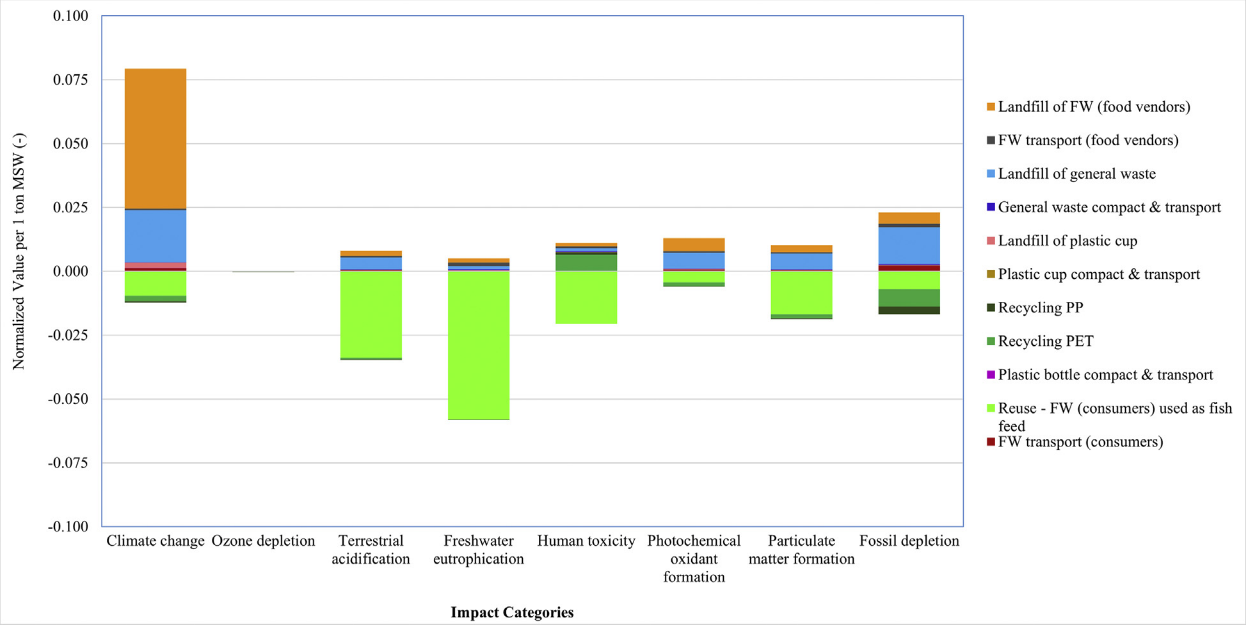

Figure 4. Normalized value of life cycle impact assessment (LCIA) results from Scenario 1: Previous scenario before the Chula Zero Waste Project (remark: FW, food waste).

and phosphorus (K) compounds. According to Wong et al. (2016), utilizing food waste as fish feed or processing it into pellets is safer than using commercial pellets due to mercury, PAHs, and DDTs in fish flesh.

3.1.2. *Current scenario (S2) under the Chula Zero Waste Project*

In this scenario, separating waste in CU canteens improved waste management, reducing landfill waste by 34%. These results show that the environmental burden of any impact category is minimal, except for climate change, which is mainly caused by landfill methane emissions, as shown in Figure 5. The Chula Zero Waste Project showed that recycling rates increased, plastic bags and plastic cups decreased to nearly zero, and food waste that was not mixed with general waste decreased. These results showed a significant reduction in overall waste volume over the past 4 years, which is associated with the decrease in waste sent to landfill. It is observed that global warming will be drastically reduced by expanding recycling. As shown in Figure 5, the greatest impact is caused by landfilling general waste from both consumers and food vendors. The highest impact caused by landfill is climate change; landfill gas from biodegradable waste contributes substantially to methane in the atmosphere, which has a significant impact on the greenhouse. A significant cause of ozone layer depletion is methane emissions from biodegradable waste landfills (Zangmo, 2017) and fuel-intensive transportation (Borrion et al., 2012).

In addition, turning food waste into fish feed provides the greatest environmental benefits. This option reduces freshwater eutrophication and terrestrial acidification. Wong et al. (2016) showed that utilizing food waste directly as fish feed or processing it into pellets was safer than using commercial pellets due to mercury, PAHs, and DDTs in fish flesh.

As shown in Figure 5, switching from plastic to paper cups (Chula zero-waste cups) reduces environmental impact because the used paper cups are used for nursery bags and compost. This reduces the potential impacts of the plastic manufacturing process, landfilling, nursery bag production, and chemical fertilizer production.

3.1.3. *Future scenario (S3) under the Chula Zero Waste Project*

S3 shows the impact of replacing landfill with RDF, which is utilized in cement production as a substitute for coal. The main effect of recycling plastic (PET) is human toxicity, as shown in Figure 6.

Most of the environmental benefits come from the use of waste and coal as fuel in the production of RDF. This reduces or compensates for the use of coal. Lima et al. (2018) report that using RDF as a substitute for conventional fuels (e.g., coal or petroleum coke) in the cement industry saves fossil fuels and reduces cumulative energy demand, GHG emissions, and other environmental effects. Reza et al. (2013) also confirmed that RDF production and utilization consumed less energy than hard coal, resulting in CO_2eq emissions of 863–888 kg/ton of clinker.

3.2. *Comparison of the distribution of environmental impacts among S1, S2, and S3*

The results of the LCA normalization analysis for each impact category across all scenarios are shown in Figure 7. When all of the impacts using the ReCiPe Midpoint (H) V1.13/World Recipe H method are compared, it can be seen that S1 has the greatest environmental burden, followed by S2, and S3 has the least impact. S3 provided the greatest environmental benefits, followed by S2. This is most likely due to the fact that the future scenario is based on the current waste management system in the CU canteens, which has responded to the policy of the Chula Zero Waste Project by reducing and separating waste more efficiently. The sequence of scenarios, from best to worst in terms of aggregated environmental impact, was S3, S2, then S1. It can be concluded that S3 is the best scenario for waste management, and S1 is the worst.

4. Discussion

S1 had the highest positive values of environmental burden on climate change, photochemical oxidant formation, and fossil depletion as shown in Figure 7. This observation is due to the fact that S1 lacked an efficient waste sorting system and had a lower recycling rate than S2 and S3. In this study, the largest source of atmospheric CH_4 was landfilling. CH_4 was produced in landfills from biodegradable waste, which significantly contributed to the amount of CH_4 in the atmosphere and had a significant impact on the greenhouse effect (Reza et al., 2013). In this study, it was observed that the level of recycling had the most considerable advantages in terms of global warming and fossil depletion. As a result, the amount of waste in S2 was reduced by 34% when compared with S1. Furthermore, RDF was used to manage waste in this scenario, and as a result, waste did not end up in landfills. When the amount of waste disposed in landfills decreases, the impact of waste on climate change, photochemical oxidant formation, and fossil depletion will also

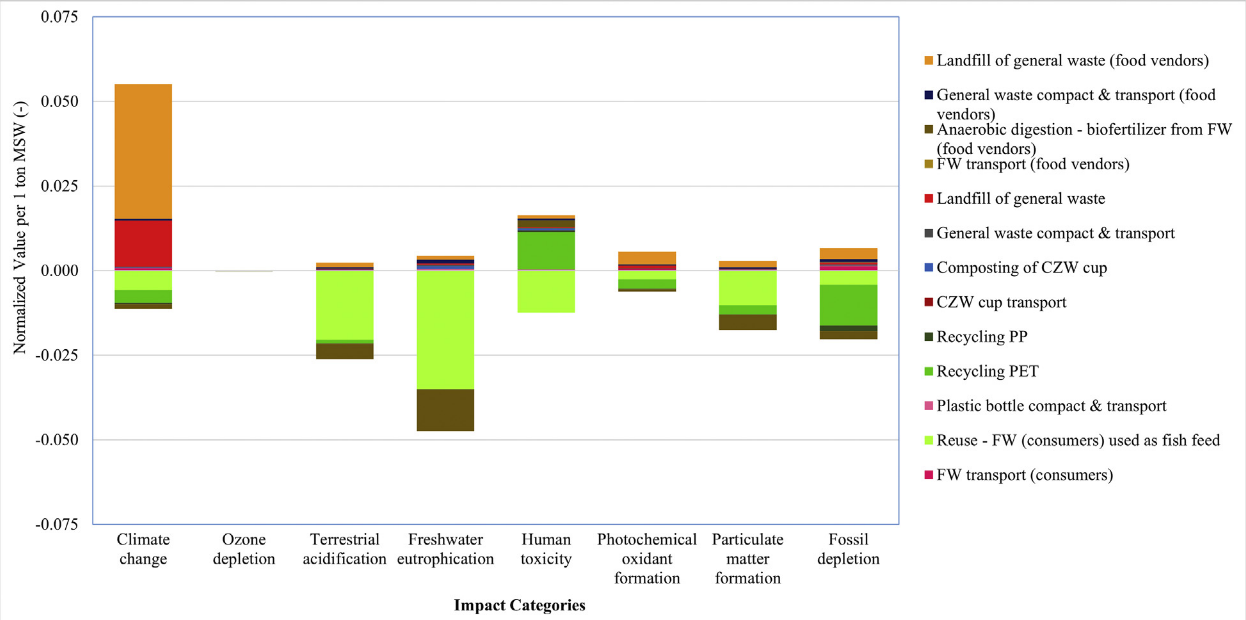

Figure 5. Normalized value of life cycle impact assessment (LCIA) results from Scenario 2: Current scenario under the Chula Zero Waste Project (remark: FW, food waste; CZW, Chula Zero Waste).

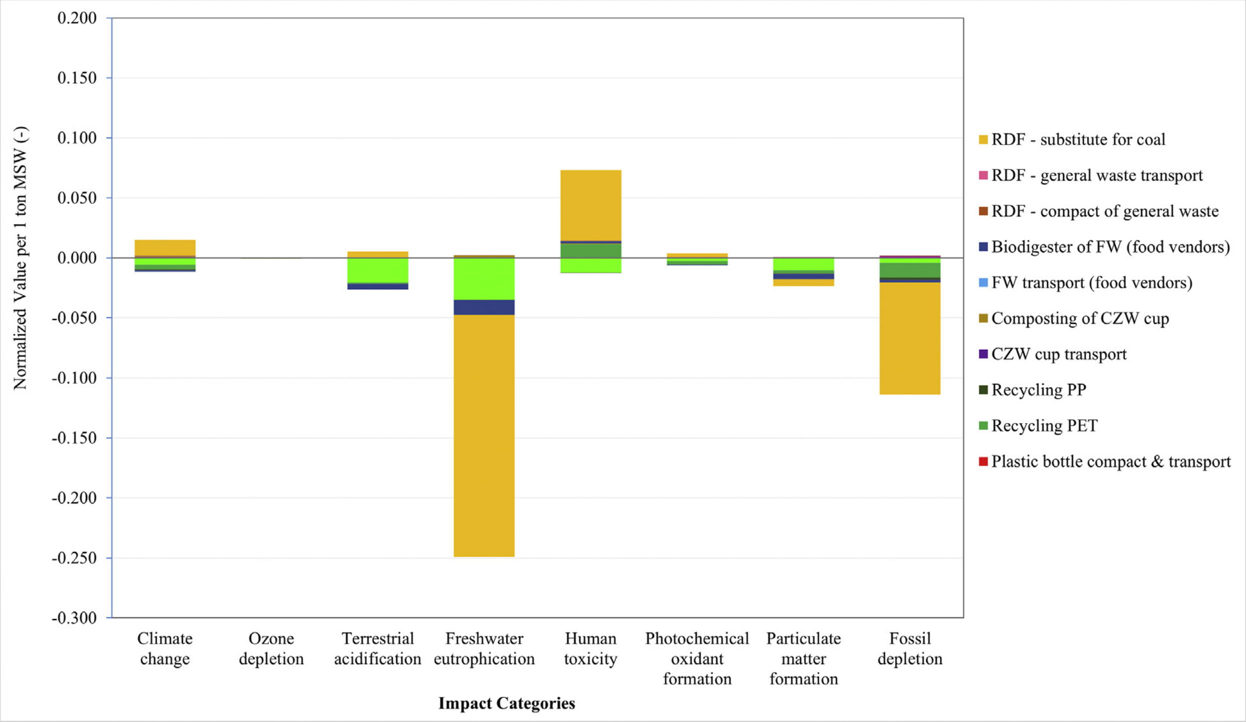

Figure 6. Normalized value of life cycle impact assessment (LCIA) results from Scenario 3: Future scenario under the Chula Zero Waste Project (remark: FW, food waste; CZW, Chula Zero Waste; RDF, refuse-derived fuel).

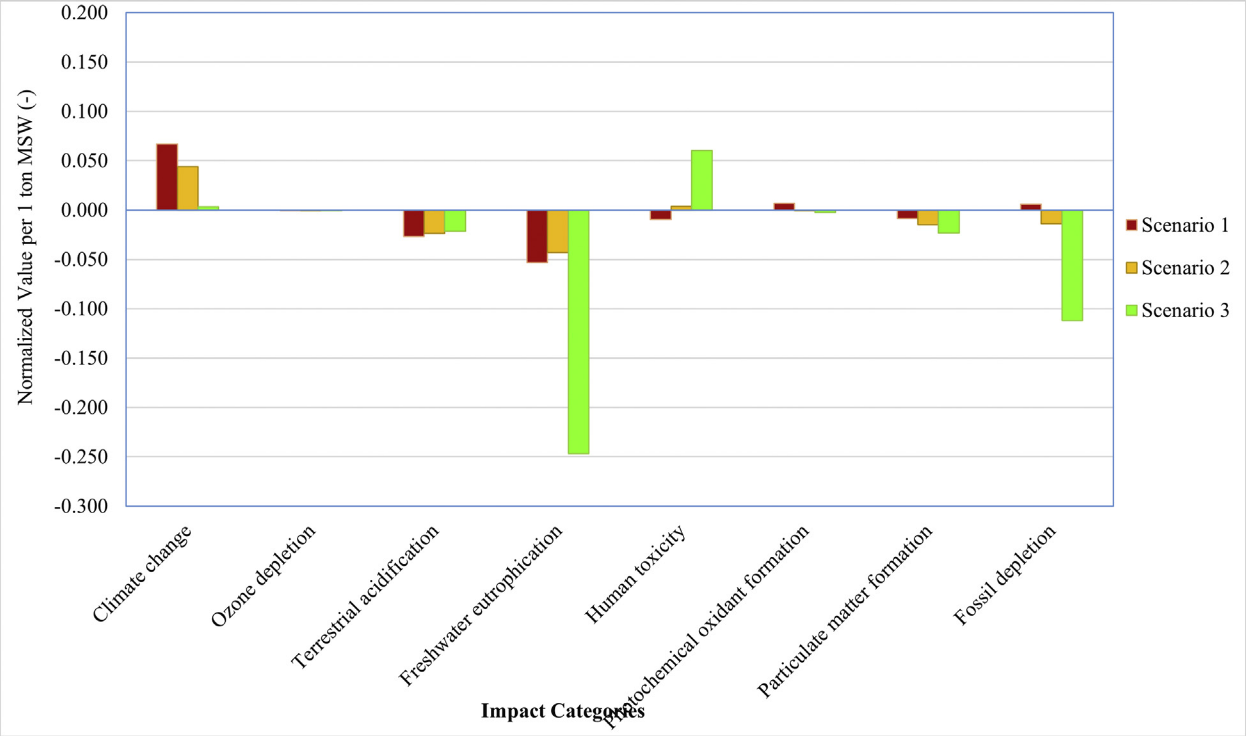

Figure 7. Comparison of the contribution of the life cycle impact assessment (LCIA) normalization analysis in the three scenarios: S1, S2, and S3.

be reduced (Reza et al., 2013; Zangmo, 2017). S3 had the highest benefit for freshwater eutrophication, particulate matter formation, and fossil depletion since it avoided landfilling of general waste, which turned into RDF and used as a coal substitute. RDF production provided the greatest potential for reducing freshwater eutrophication, particular matter formation, and fossil depletion. $PM_{2.5}$ was emitted during the combustion of RDF. The impact of direct emissions on particulate matter emphasizes the importance of efficient fume treatment systems in reducing particulate emissions from the combustion of biomass and wastes. S1 provided the most environmental benefit in terms of terrestrial acidification because it avoided the production of fish feed by repurposing food waste as animal feed, which reduced terrestrial acidification. S3 had the lowest environmental benefit in terms of terrestrial acidification because RDF combustion in a boiler emits SOx and NOx, which is a major contributor to acidification. In addition, S3 showed the greatest environmental burden on human toxicity with respect to toxic substances, and this burden was caused by the use of RDF as a fuel in a boiler. In this study, the highest human toxicity was caused by RDF combustion. Air- and water-borne metals, HCl, HF, N_2O, and NOx emissions from RDF combustion, which were mainly plastic components, were toxic to humans. In S3, the avoided impact of RDF was lower than the process emissions on human toxicity (Longo et al., 2020).

Based on normalization results for all impact categories across scenarios, S1 had the greatest environmental burden because 44% of waste was disposed of in landfills, which created the greatest environmental impacts. As confirmed by numerous studies, Coelho and Lange (2018) demonstrated that Scenario 1, which involved landfilling MSW in Rio de Janeiro, had the worst environmental impacts. Furthermore, Yay (2015) found that landfilling was the worst final waste disposal option, whereas composting and material recovery performed better for solid waste management in Sakarya, Turkey. When environmental benefits were considered, S3 had the greatest benefits, followed by S2. Due to the conversion of waste in S2 to RDF in S3, S3 generated zero waste for landfill. This was because S3 was based on the current waste management system in CU canteens, which responded to the Chula Zero Waste Project's policy of reducing and separating waste more efficiently. According to Sukholthaman and Sharp (2016), this study employed a system dynamics model to evaluate the impact of effective source separation on waste collection and transportation in Bangkok, Thailand. Their results showed that source separation affected the amount of recyclable waste, organic waste, landfilled waste, cost, and collection service efficiency. In this study, the best to worst scenarios in terms of aggregated environmental impact were S3, S2, and S1. S3 was the best waste management scenario, whereas S1 was the worst.

4.1. Comparison to other LCA studies

In comparison with similar studies in Brazil and Turkey by Coelho and Lange (2018) and Yay (2015), respectively, they demonstrated that landfill, which represents the current state of the MSW system, has the worst environmental impacts. Similarly, this study mirrored both studies. In addition, when comparing the S3 scenario of this study with a similar study in Brazil by Lima et al. (2018), they reported that RDF produced from MSW and utilized in cement production contributed to huge savings due to avoided petroleum coke utilization in almost all impact categories except for human toxicity (non-cancer). In this study, RDF reduced impacts in four of eight categories except for climate change, acidification, photochemical oxidant formation, and human toxicity. The different results depend strongly on the composition of waste in the RDF of both studies.

5. Conclusions

This study is a part of a larger project to identify the best MSW management practices in CU canteens using LCA.

The highest environmental impacts were observed in S1 landfilling, whereas S3 had the least environmental impact because no waste was disposed of in landfills and RDF was implemented. Food waste, which accounts for the majority of waste in CU canteens, can be used as nutrients for animal feed and compost to divert it from S2 and S3 landfills. Zero waste to landfills in S3 can reduce environmental and economic losses by converting low-humidity, high-calorific waste to RDF for the cement industry. According to the findings, the most environmentally effective MSW strategy for CU canteens is to reduce and separate waste at the source and recover materials instead of disposing of mixed waste in landfills.

Based on the results, we offer policymakers recommendations for enhancing the environmental sustainability of waste management systems in universities. First, the concept of zero waste to landfills should be popularized. Second, waste separation at sources should be encouraged. Finally, RDF can substitute for coal or petroleum coke in cement plants. RDF is more environmentally friendly compared to coal. Therefore, the use of RDF should be promoted as a coal substitute, and landfill waste should be reduced.

Moreover, it will help in achieving SDG for sustainable cities (SDG 11), responsible consumption and production (SDG 12), and climate action (SDG 13). The findings of the study provide CU canteen with a viable option for planning waste management and achieving a "zero waste to landfill" scenario. Further research could look into detailed frameworks to improve sustainable MSW management by creating a better balance between the environment, the economy, and society, as well as interventions aimed at MSW reduction, recycling, and sending zero waste to landfills.

Declarations

Author contribution statement

Nuta Supakata: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Palaporn Sukma; Kanokpish Srinok: Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Seksan Papong: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Funding statement

Dr Nuta Supakata was supported by Thailand Science research and Innovation Fund Chulalongkorn University [CU_FRB65_bcg (10) _078_23_08].

Data availability statement

Data will be made available on request.

Declaration of interest's statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

Acknowledgements

The authors gratefully acknowledge the Chula Zero Waste Project team: Dr. Sujitra Vassanadumrongdee (PM), Mr. Korb Limsuwan (PM), and the CU office of physical resource management staff, Tapanee Sangpatch, Pathompong Vibhatabandhu, Ramonporn Piyapanan, Navapan Assavasuntakul, and PR staff for providing their support. The helps of providing database and software of National Metal and Materials Technology Center used in this investigation are gratefully acknowledged. The authors also would like to thank Assistant Professors Dr. Sarawut Srithongouthai and Dr. Vorapot Kanokantapong for their kindly suggestions and Mr. Songkran, Mrs. Neon, and Mrs. Penwipha and his son for their assistance and useful waste recycling information. Gratitude is also extended to Mr. Manachai and Mrs. Monthita, who shared information about bringing food waste to feed the fish.

References

Allesch, A., Brunner, P.H., 2014. Assessment methods for solid waste management: a literature review. Waste Manag. Res. 32, 461–473.

Borrion, A.L., Khraisheh, M., Benyahia, F., 2012. Environmental life cycle impactassessment of gas-to-liquid processes. In: Proceedings of the 3rd Gas Processing Symposium, March 5-7, 2012. Elsevier B.V, Qatar.

Brancoli, P., Rousta, K., Bolton, K., 2017. Life cycle assessment of supermarket food waste. Resour. Conserv. Recycl. 118, 39–46.

Chulalongkorn University, 2020. Chulalongkorn University Sustainability Report 2018-2020. Available online at: http://www.green.chula.ac.th/wp-content/uploads/2019/09/Chulalongkorn-University-Sustainability-Report-2016-2017-Beta-Version.pdf.

Clift, R., 2006. Sustainable Development and its implication for chemical engineering. Chem. Eng. Sci. 61, 4179–4187.

Clift, R., 2013. System approaches: life cycle assessment and industrial ecology. In: Pollution 5th Edition: Causes, Effects and Control.

Coelho, L.M.G., Lange, L.C., 2018. Applying life cycle assessment to support environmentally sustainable waste management strategies in Brazil. Resour. Conserv. Recycl. 128, 438–450.

Cui, H., Sošić, G., 2019. Recycling common materials: effectiveness, optimal decisions, and coordination mechanisms. Eur. J. Oper. Res. 274, 1055–1068.

Finnveden, G., Johannsson, J., Lind, P., Moberg, A., 2005. Life cycle assessment of energy from solid waste - Part 1: general methodology and results. J. Clean. Prod. 13, 213–229.

García-Herrero, L., Menna, F., Vittuari, M., 2019. Food waste at school. The environmental and cost impact of a canteen meal. Waste Manag. 100, 249–258.

Giugliano, M., Cernuschi, S., Grosso, M., Rigamonti, L., 2011. Material and energy recovery in integrated waste management systems. An evaluation based on life cycle assessment. Waste Manag. 31, 2092–2101.

Goedkoop, M., Heijungs, R., Huijbergts, M., 2009. ReCiPe 2008. Report 1: Characterization. Ministry of Housing, Spatial Planning and Environment, the Netherlands.

Heijungs, R., Guinée, J., Kleijn, R., Rovers, V., 2007. LCA methodology bias in normalization: causes, consequences, detection and remedies. Int. J. Life Cycle Assess. 12, 211–216.

ISO, 2006a. ISO 14040: Environmental Management-Life Cycle Assessment, Principles and Guidelines. International Organization for Standardization, Geneva.

ISO, 2006b. ISO 14044: Environmental Management-Life Cycle Assessment, Life Cycle Impact Assessment. International Organization for Standardization, Geneva.

Kaza, S., Yao, L., Bhada-Tata, P., Woerden, F.V., 2018. What a Waste 2.0: a Global Snapshot of Solid Waste Management to 2050. In: Urban Development. World Bank. © World Bank, Washington, DC. Available online at: https://openknowledge.worldbank.org/handle/10986/30317%20License:%20CC%20BY%203.0%20IGO.

Lima, P.D.M., Colvero, D.A., Gomes, A.P., Wenzel, H., Schalch, V., Cimpan, C., 2018. Environmental assessment of existing and alternative options for management of municipal solid waste in Brazil. Waste Manag. 78, 857–870.

Liu, G., Hao, Y., Dong, L., Yang, Z., Zhang, Y., Ulgiati, S., 2017. An emergy-LCA analysis of municipal solid waste management. Resour. Conserv. Recycl. 120, 131–143.

Longo, S., Cellura, M., Girardi, P., 2020. Life cycle assessment of electricity production from refuse derived fuel: a case study in Italy. Sci. Total Environ. 738, 139719.

Office of the National Economic and Social Development Board, 2016. Office of the Prime Minister, Bangkok, Thailand. In: The Twelfth National Economic and Social Development Plan (2017-2021). Available online at: https://www.nesdc.go.th/nesdb_en/download/article/article_20170705111314.pdf.

Rafizul, I.M., Alamgir, M., 2012. Characterization and tropical seasonal variation of leachate: results from landfill lysimeter studied. Waste Manage 32, 2080–2095.

Reza, B., Soltani, A., Ruparathna, R., Sadiq, R., Hewage, K., 2013. Environmental and economic aspects of production and utilization of RDF as alternative fuel in cement plants: a case study of Metro Vancouver Waste Management. Resour. Conserv. Recycl. 81, 105–114.

Simachaya, W., 2020. Solid Waste during COVID-19. Thailand Environment Institute. Available online at: http://www.tei.or.th/en/blog/detail.php?blog/id=49.

Singh, C.K., Kumar, A., Roy, S.S., 2018. Quantitative analysis of the methane gas emissions from municipal solid waste in India. Sci. Rep. 8, 2913.

Sukholthaman, P., Sharp, A., 2016. A system dynamics model to evaluate effects of source separation of municipal solid waste management: a case of Bangkok, Thailand. Waste Manage 52, 50–61.

Wang, D., He, J., Tang, Y.-T., Higgitt, D., Robinson, D., 2020. Life cycle assessment of municipal solid waste management in Nottingham, England: past and future perspectives. J. Clean. Prod. 251, 119636.

Wong, M.-H., Mo, W.-Y., Choi, W.-M., Cheng, Z., Man, Y.-B., 2016. Recycle food wastes into high-quality fish feeds for safe and quality fish production. Environ. Pollut. 219, 631–638.

Yay, A.S.E., 2015. Application of life cycle assessment (LCA) for municipal solid waste management: a case study of Sakarya. J. Clean. Prod. 94, 284–293.

Zangmo, C., 2017. Life Cycle Assessment of MSW Management in Paro District, Bhutan. Sirindorn International Institute of Technology, Thammasat University. Thesis.

Zhang, H., Li, S., Wei, D., He, L., Chen, J., Sun, C., Vuppaladadiyam, A.K., Duan, H., 2021. Characteristics, environmental impact, and reduction strategies of food waste generated by young adults: case study on university canteens in Wuhan, China. J. Clean. Prod. 32, 128877.

Zorpas, A.A., Lasaridi, K., Pociovalisteanu, D.M., Loizia, P., 2018. Monitoring and evaluation of prevention activities regarding household organics waste from insular communities. J. Clean. Prod. 172, 3567–3577.