CHEMICAL ENGINEERING TRANSACTIONS
VOL. 97, 2022

A publication of
AIDIC
The Italian Association
of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Jeng Shiun Lim, Nor Alafiza Yunus, Jiří Jaromír Klemeš

ISBN 978-88-95608-96-9; **ISSN** 2283-9216

DOI: 10.3303/CET2297069

Environmental Hotspots Evaluation of Municipal Solid Waste Treatment Facilities in Human Health and Climate Change

Min Yee Chin[a], Chew Tin Lee[b], Kok Sin Woon[a,*]

[a]School of Energy and Chemical Engineering, Xiamen University Malaysia, Jalan Sunsuria, Bandar Sunsuria, 43900 Sepang, Selangor Darul Ehsan, Malaysia.
[b]School of Chemical and Energy Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor Darul Takzim, Malaysia.
koksin.woon@xmu.edu.my

Due to waste heterogeneity, different treatment facilities are needed to treat various types of waste. The major sub-processes in a waste treatment facility that incur high environmental burdens and offset as value-added resources have yet to be feasibly realized at a large scale. This study aims to identify the environmental hotspots of four commonly-used solid waste treatment facilities (open landfill, sanitary landfill, tunnel composting, mechanical material recovery facility) with a focus on human health (fine particulate matter formation, human carcinogenic toxicity, and human non-carcinogenic toxicity) and climate change impacts through life cycle assessment. The major environmental hotspots for open landfills and sanitary landfills are the landfill gas emission in global warming (601.8 kg CO_2-eq/t MSW and 353.9 kg CO_2-eq/t MSW); tunnel composting is the electricity consumption (57 - 84 % of total performance); while mechanical material recovery facility is the recovered material (99.6 - 99.8 % of total performance). Recommendations are proposed to reduce the major environmental burdens of the waste treatment facilities. This study provides practical scenarios to policymakers in formulating a sustainable municipal solid waste management framework with reduced impacts on human health and climate change.

1. Introduction

Solid waste management is a pressing burden for sustainable city development. In 2016, around 1.6×10^9 t CO_2-eq of greenhouse gases (GHGs) was generated from solid waste management treatment, primarily from open dumping and landfill disposal (Kaza et al., 2018). Various solid waste treatment facilities are implemented to treat the solid waste appropriately. In line with improving environmental sustainability, the environmental impacts of the solid waste treatment facilities are evaluated to explore the feasibility of implementing the waste treatment facilities. Mah et al. (2017) found that disposal of concrete waste in landfills emits the highest carbon emission compared to recycling as road base material and reused concrete, which is more environmentally preferable. The sub-process with the highest GHG emissions is not identified where the improvement in a particular process could not be made. Nordahl et al. (2020) assessed the climate change and human health trade-off between landfilling and biological treatment of organic waste. This study quantified the greenhouse gas and air pollutant inventory in each treatment facility where the specific hotspot is not determined for impact mitigation. Silva et al. (2021) compared the environmental performance of refuse-derived fuel production from MSW with the business-as-usual municipal solid waste (MSW) management system. The study only suggested that refuse-derived fuel used in cement kiln production is vital in waste treatment, offering environmental benefits. Cudjoe and Acquah (2021) revealed the total global warming, acidification, and dioxin emission potential of incineration in 56 African countries and compared them without pointing out the burdening environmental process. Woon et al. (2021) conducted a life cycle assessment study to justify the environmental feasibility of the food waste valorization technologies. This study evaluated various valorization technology scenarios in different recovered product substitutions. Dal Pozzo and Cozzani (2021) evaluated and compared the environmental footprints of three wet scrubber treatment alternatives in waste-to-energy facilities where only the avoided product was quantified separately from the entire treatment process.

Paper Received: 15 June 2022; Revised: 28 July 2022; Accepted: 31 July 2022
Please cite this article as: Chin M.Y., Lee C.T., Woon K.S., 2022, Environmental Hotspots Evaluation of Municipal Solid Waste Treatment Facilities in Human Health and Climate Change, Chemical Engineering Transactions, 97, 409-414 DOI:10.3303/CET2297069

This literature assessed the environmental impacts of the solid waste treatment facility without looking into the sub-processes. There is a lack of study exploring the environmental hotspots of the solid waste treatment facilities with the value-added resources taken into account. This study aims to identify the environmental hotspots of various solid waste treatment facilities and investigate the major cause of the environmental loads. Analyzing the environmental hotspots by life cycle assessment, this study can facilitate the development of environmentally efficient MSW management by presenting the environmental hotspots to the stakeholders so that the treatment selection or technological improvement could be made to reduce the adverse effect on the climate and human health.

2. Methodology

This research takes Malaysia as a case study to assess the environmental hotspots of solid waste treatment facilities, with an average waste generation rate of 1.17 kg/cap/d (PEMANDU, 2015). The estimated MSW composition for Malaysia in 2012: food (45 %), plastic (13 %), paper (9 %), diapers (12 %), garden (6 %), and others (16 %) (PEMANDU, 2015). In Malaysia, 71.5 % of MSW is disposed to open landfills, while the remaining are treated in sanitary landfills (10 %), composting (1 %), and material recovery facilities (17.5 %) (Kaza et al., 2018). This study is conducted following the life cycle assessment framework (ISO 14040/44), which consists of four phases: a) goal and scope definition, b) inventory analysis, c) impact assessment and d) interpretation.

2.1 Goal and scope definition

This study aims to identify the environmental hotspots, including the major cause of the environmental burden, of the solid waste disposal and treatment facilities, taking into account the value-added resources. The studied solid waste disposal and treatment facilities include open landfill (OLF), sanitary landfill (SLF), tunnel composting (TComp), and mechanical material recovery facility (MRF). It is assumed that these facilities are operated for 30 y in Malaysia. The environmental hotspot assessment is carried out within the system boundary from waste disposed at the facility to the end-of-life of the generated products, such as substituting virgin resources with the value-added resources generated during the waste treatment process (Figure 1). The environmental impacts of each hotspot are evaluated based on one t of feedstock as the functional unit (FU) since waste treatment is the main function of these facilities. All the inputs and outputs are referred to the FU to ensure the fairness of the comparison.

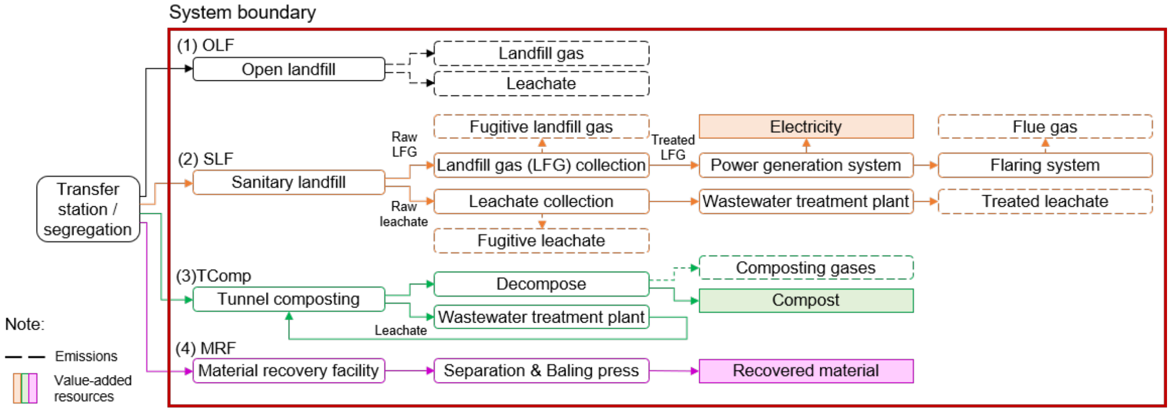

Figure 1: The flow diagram and system boundary of the studied waste disposal and treatment facilities.

2.2 Life cycle inventory analysis

The operational data for each solid waste treatment facility are collected from several sources, such as governmental portals, project reports, and peer-reviewed journal articles. The Ecoinvent 3.8 database is applied as the primary source for the background data. The data inventory for each facility, per FU, is tabulated in Table 1. The data inventories present the input and output parameters of the facilities' hotspots within the system boundary, including energy and material consumption, emissions, and value-added resources production.

The studied OLF is a waste disposal site without any landfill gas recovery and leachate collection system. The annual treatment capacity of OLF is 14.2 Mt/y. The landfill gases and leachate produced are emitted to the atmosphere and groundwater. The amount of methane generated is calculated from the waste model of the 2006 IPCC guidelines (2019 Refinement), while the leachate production is around 150 L/t of MSW (Kamaruddin et al., 2017). The constituents of leachate are adopted from Hussein et al. (2021).

For SLF, the annual treatment capacity is 14.2 Mt/y. The landfill gas is collected to generate electricity while the leachate is treated, meeting the discharge standards before releasing it into the waterway. The calculation for landfill gas and leachate obtained are similar to OLF. The landfill gas generated is assumed to be zero-captured for 1 - 2 y, 40 % captured for 3 - 10 y, and 90 % recovery for the next twenty years, while 5 % of the leachate produced is assumed to be fugitive (Woon and Lo, 2013). The collected landfill gas is used to generate electricity to replace the electricity from the grid. The energy recovery system's operational data is sourced from Clean Development Mechanism (2020).

Table 1: Data inventory for the four studied municipal solid waste treatment facilities

Hotspot	Parameter	Unit	Value	Hotspot	Parameter	Unit	Value
			Open landfill (OLF)				
Landfill gas	Methane	kg/t	16.5	Leachate	Arsenic	kg/t	2.61×10^{-5}
	Carbon dioxide	kg/t	40.8		Cadmium	kg/t	9.64×10^{-7}
	Nitrogen	kg/t	1.73		Copper	kg/t	1.72×10^{-5}
	Oxygen	kg/t	0.33		Chromium	kg/t	2.46×10^{-5}
	Ammonia	kg/t	0.175		Nickel	kg/t	2.47×10^{-5}
	Sulfides	kg/t	0.33		Zinc	kg/t	1.41×10^{-4}
	NMOCs	kg/t	0.533		Manganese	kg/t	1.32×10^{-4}
					Iron	kg/t	5.83×10^{-3}
	Hydrogen	kg/t	4.12×10^{-3}		Lead	kg/t	2.49×10^{-5}
	Carbon monoxide	kg/t	5.77×10^{-2}		Selenium	kg/t	1.98×10^{-5}
			Sanitary landfill (SLF)				
Fugitive landfill gas	Methane	kg/t	10.3	Fugitive leachate	Cadmium	kg/t	2.7×10^{-8}
	Carbon dioxide	kg/t	25.4		Copper	kg/t	2.14×10^{-8}
	Nitrogen	kg/t	1.08		Chromium	kg/t	4.14×10^{-7}
	Oxygen	kg/t	0.205		Nickel	kg/t	3.13×10^{-7}
	Ammonia	kg/t	0.109		Zinc	kg/t	5.64×10^{-7}
	Sulfides	kg/t	0.205		Manganese	kg/t	3.23×10^{-7}
	NMOCs	kg/t	0.332		Iron	kg/t	9.87×10^{-6}
	Hydrogen	kg/t	2.57×10^{-3}		Lead	kg/t	6.98×10^{-8}
	Carbon monoxide	kg/t	3.59×10^{-2}		Selenium	kg/t	7.73×10^{-7}
Power generation system	Electricity consumption	kWh/t	4.05	Treated leachate	Arsenic	kg/t	7.13×10^{-6}
	Electricity generation	kWh/t	31.3		Cadmium	kg/t	1.43×10^{-6}
Flaring system	Electricity consumption	kWh/t	0.156		Copper	kg/t	2.85×10^{-5}
	PM_{10}	kg/t	3.94×10^{-6}		Chromium	kg/t	7.13×10^{-6}
	$PM_{2.5}$	kg/t	1.48×10^{-6}		Nickel	kg/t	2.85×10^{-5}
	Sulfur dioxide	kg/t	7.87×10^{-6}		Zinc	kg/t	2.85×10^{-4}
	Nitrogen dioxide	kg/t	6.89×10^{-6}		Manganese	kg/t	2.85×10^{-5}
	Ozone	kg/t	9.84×10^{-6}		Iron	kg/t	7.13×10^{-4}
	Carbon monoxide	kg/t	9.84×10^{-4}		Lead	kg/t	1.43×10^{-5}
Fugitive leachate	Arsenic	kg/t	6.48×10^{-7}		Selenium	kg/t	2.85×10^{-6}
			Tunnel composting (TComp)				
Energy and material consumption	Electricity	kWh/t	95	Gaseous emission	Ammonia	kg/t	0.39
	Diesel	kg/t	3.98		VOCs	kg/t	1.21
	Water	kg/t	330		Carbon monoxide	kg/t	0.1
	Lubricating grease	kg/t	1.04×10^{-2}		Carbon dioxide, biogenic	kg/t	350
	Motor oil	kg/t	4×10^{-3}		Carbon dioxide, fossil	kg/t	7.30
	Hydraulic oil	kg/t	4×10^{-3}	Compost	Min. N fertilizer	kg/t	3.60
Gaseous emission	Methane	kg/t	3.4×10^{-2}		Min. P_2O_5 fertilizer	kg/t	0.68
	Nitrogen oxide	kg/t	0.11		Min. K_2O fertilizer	kg/t	1.98
			Mechanical material recovery facility (MRF)				
Energy and material consumption	Electricity	kWh/t	5.55	Avoided product	Paper	kg/t	244
	Diesel	kg/t	0.588		Plastic	kg/t	419
	Wire	kg/t	0.6		Glass	kg/t	90.3
					Metal	kg/t	76.4

Note: The 9 heavy metals include antimony, arsenic, lead, chromium, cobalt, copper, manganese, nickel, and vanadium. NMOCs: Non-methane organic compounds, VOCs: Volatile organic compounds.

A TComp plant from Lu et al. (2020) is adopted in this study. This TComp plant is assumed as a centralized composting plant. Only organic waste (OW), such as food, garden, and yard waste, is treated in the TComp plant with an average of 7.35 Mt/y of treatment capacity. Gases and leachate are treated, released into the air, and circulated back to composting. Compost is generated from the composting process used as biofertilizer to substitute the conventional chemical fertilizer. The NPK value of compost is estimated as N: 3.6 kg, P: 0.68 kg, and K: 1.98 kg/t organic waste.

The studied MRF is a single-stream process facility. The facility has a treatment capacity of 4.92 Mt/y. The operational data is referred to by Pressley et al. (2015). The recyclable materials involve in this facility include plastics, papers, glass, and metals. The overall material recovery rate is 90 %. The recovered materials are compressed and baled in the end and sent out for manufacturing. The recovered materials are turned into pellets or scraps and used to replace the virgin materials consumption for a new product.

2.3 Life cycle impact assessment

The life cycle assessment model is constructed by SimaPro 9.2 software. The human health and climate change impacts of the solid waste treatment facilities are evaluated through the ReCiPe 2016 characterization method. The assessed impact includes global warming, fine particulate matter formation, human carcinogenic toxicity, and human non-carcinogenic toxicity, the most representative of climate change and human health issues from different damage pathways (Mulya et al., 2022).

3. Results and discussion

Figure 2 presents the climate change and human health impacts' results in global warming (GW), fine particulate matter formation (PMF), human carcinogenic toxicity (HCT), and human non-carcinogenic toxicity (HnCT). The positive results indicate the burden effects while vice versa for negative results. OLF has the highest environmental burden in GW, while tunnel composting is the most environmentally destructive treatment method in PMF, HCT, and HnCT. Mechanical material recovery facility offers the highest environmental benefits in all impact categories. OLF and SLF incur 601.8 and 353.9 kg CO_2-eq/t MSW, respectively, in GW (the top two highest environmental burdens). This is mainly caused by landfill gas (LFG) emissions, which comprise high GHGs such as CH_4 and CO_2. Lin et al. (2022) reported that LFG recovery is crucial as it can reduce 71.3 % of CH_4 emissions. The high-efficient LFG collection pipeline is recommended to reduce the environmental loads from the SLF's fugitive LFG emissions (Ooi et al., 2021). OLF and SLF do not significantly impact fine particulate matter formation, human carcinogenic toxicity, and human non-carcinogenic toxicity compared to other waste treatment facilities. Landfill gas contains a lesser degree of airborne substances that causes respiratory disease and cancer in human.

The overall performance of SLF offers an environmentally beneficial impact on PMF, HCT, and HnCT. Electricity generated from SLF contributes to environmental savings by reducing the fossil-based electricity that undergoes extraction and burning of fossil fuels, lowering the release of nitrogen oxides into the air and zinc and chromium VI into the groundwater. The avoided impact contributed by the displacement of fossil-based electricity does not significantly outweigh the environmental burden caused by the fugitive LFG emissions. This finding contrasts with Lin et al. (2022), which showed that sanitary landfill significantly benefits GW, PMF, HCT, and HnCT. The difference is due to the efficiency of LFG conversion to electricity. The conversion rate for this study is approximately 3 %, calculated from Clean Development Mechanism (2020), while Lin et al. (2022) assumed that all the collected LFG is sent to a gas turbine for electricity generation. Increasing the conversion rate of LFG or adding more gas turbines in the plant would increase the amount of electricity generated, resulting in higher conventional electricity displacement, contributing to more environmental benefits.

In all impact categories, TComp incurs adverse environmental performance: global warming (63.3 kg CO_2-eq/t OW), fine particulate matter formation (0.25 kg $PM_{2.5}$-eq/t OW), human carcinogenic toxicity (1.91 kg 1,4-DCB/t OW), human non-carcinogenic toxicity (9.07 kg 1,4-DCB/t OW), mainly incurred by electricity consumption. Lu et al. (2020) claimed that home composting or centralized windrow composting has 1.4-1.7 times and 1.1-8.1 times more advantages than TComp on global warming and human carcinogenic toxicity, respectively, as home composting and centralized windrow composting require lesser electricity consumption than TComp. Compost gas emission is another environmental hotspot significantly contributing to the PMF (40 % of the total burden incurred by TComp). Airborne particulate matters such as ammonia and nitrogen oxides are released during the composting process, where they can be minimized by adding biochar (Lin et al., 2022). The avoided impact from the compost is insufficient to outweigh the adverse impacts caused during the composting process. This is due to the low compost yield (453 kg compost/t OW) in tunnel composting, which can only substitute a small amount of chemical fertilizer.

Mechanical MRF offers the best environmental performance in human health and climate change, contributing net environmental benefits in all assessed impact categories. Mechanical MRF contributes at least 3.8 times more beneficial impact than OLF, with -1,689 kg CO_2-eq/t feedstock in global warming, -2.6 kg $PM_{2.5}$-eq/t feedstock in fine particulate matter formation, -109 kg 1,4-DCB/t feedstock in human carcinogenic toxicity, -590 kg 1,4-DCB/t feedstock in human non-carcinogenic toxicity. Mechanical MRF incurs significantly lower environmental burdens compared to other waste treatment facilities. Mechanical MRF is unlikely to emit harmful gaseous during the mechanical waste treatment. The significant saving contributions arise from substituting recycled resources for virgin materials. After transforming into pellets or scraps, the recycled materials can be used as the raw material for manufacturing a new product. This could reduce the environmental burdens by virgin materials' extraction and manufacturing process.

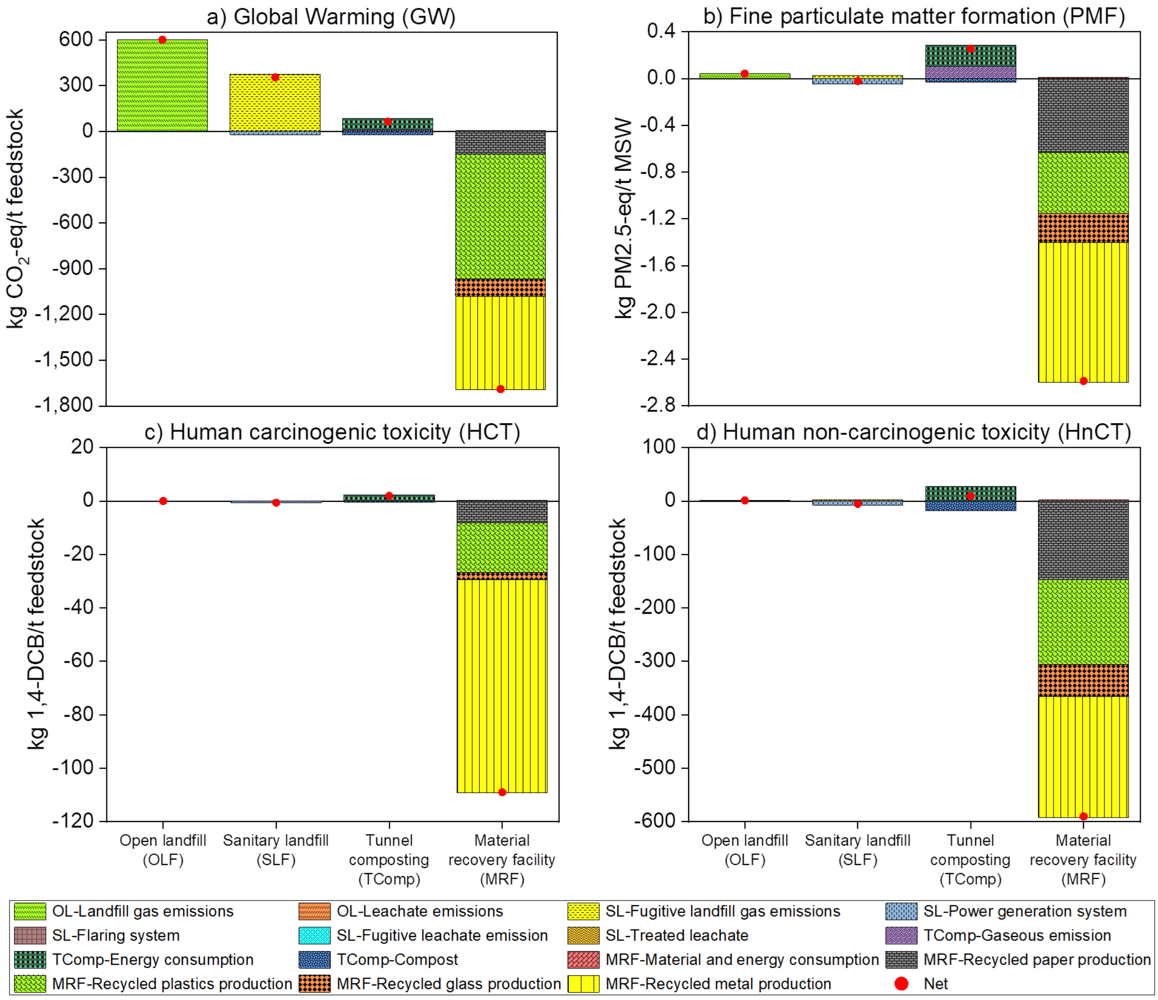

Figure 2: Climate change and human health impact on various solid waste treatment facilities. Positive values indicate the adverse effect, while negative values present the environmental saving

4. Conclusions

Environmental hotspots of various solid waste treatment facilities in human health and climate change are identified from a life cycle perspective. Results show that landfill gas emission is the major hotspot in global warming for open landfills (601.8 kg CO_2-eq/t MSW) and the sanitary landfill (353.9 kg CO_2-eq/t MSW). Electricity consumption incurred a significant burden for tunnel composting, resulting in the net performance of human health and climate change contributing adverse effects. The value-added resources produced result in the mechanical material recovery facility offering the most environmental favourable due to the environmental saving effect from the virgin material replacement. The results suggest that mechanical material recovery facility is 3.8-fold, 65.6-fold, 190,374.2-fold, and 504.2-fold more environmentally friendly in global warming, fine particulate matter formation, human carcinogenic toxicity, and human non-carcinogenic toxicity, respectively, than the open landfill. Future studies can be expanded by involving more impact categories on human health, such as ozone depletion and creation, and integrating with life cycle costing assessment.

Acknowledgements

The authors would like to thank for the financial support from the Ministry of Higher Education Malaysia through the Fundamental Research Grant Scheme (FRGS/1/2020/TK0/XMU/02/2).

References

Chanchampee, P., 2010, Methods for evaluation of waste management in Thailand in consideration of policy, environmental impact and economics, PhD Dissertation, Technical University of Berlin, Berlin, Germany.

Clean Development Mechanism, 2020, Landfill Gas Recovery and Utilization at Bukit Tagar Sanitary Landfill, Hulu Selangor in Malaysia, Kuala Lumpur, Malaysia.

Cudjoe, D., Acquah, P.M., 2021, Environmental impact analysis of municipal solid waste incineration in African countries, Chemosphere, 265, 129186.

Dal Pozzo, A., Cozzani, V., 2021, Wastewater management of wet scrubbers in waste-to-energy facilities: A life cycle analysis, Chemical Engineering Transactions, 86, 619–624.

Hussein, M., Yoneda, K., Mohd-Zaki, Z., Amir, A., Othman, N., 2021, Heavy metals in leachate, impacted soils and natural soils of different landfills in Malaysia: An alarming threat, Chemosphere, 267, 128874.

Kamaruddin, M.A., Yusoff, M.S., Rui, L.M., Isa, A.M., Zawawi, M.H., Alrozi, R., 2017, An overview of municipal solid waste management and landfill leachate treatment: Malaysia and Asian perspectives, Environmental Science and Pollution Research, 24, 26988–27020.

Kaza, S., Yao, L.C., Bhada-Tata, P., Van Woerden, F., 2018, What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050, Urban Development Series, World Bank, Washington, DC, United States.

Lin, Z., Ooi, J.K., Woon, K.S., 2022, An integrated life cycle multi-objective optimization model for health-environment-economic nexus in food waste management sector, Science of The Total Environment, 816, 151541.

Lu, H.R., Qu, X., El Hanandeh, A., 2020, Towards a better environment - the municipal organic waste management in Brisbane: Environmental life cycle and cost perspective, Journal of Cleaner Production, 258, 120756.

Mah, C.M., Fujiwara, T., Ho, C.S., 2017, Concrete waste management decision analysis based on life cycle assessment, Chemical Engineering Transactions, 56, 25–30.

Mulya, K.S., Zhou, J., Phuang, Z.X., Laner, D., Woon, K.S., 2022, A systematic review of life cycle assessment of solid waste management: Methodological trends and prospects, Science of The Total Environment, 831, 154903.

Nordahl, S.L., Devkota, J.P., Amirebrahimi, J., Smith, S.J., Breunig, H.M., Preble, C. V., Satchwell, A.J., Jin, L., Brown, N.J., Kirchstetter, T.W., Scown, C.D., 2020, Life-Cycle Greenhouse Gas Emissions and Human Health Trade-Offs of Organic Waste Management Strategies, Environmental Science & Technology, 54(15), 9200–9209.

Ooi, J.K., Woon, K.S., Hashim, H., 2021, A multi-objective model to optimize country-scale municipal solid waste management with economic and environmental objectives: A case study in Malaysia, Journal of Cleaner Production, 316, 128366.

Performance Management And Delivery Unit (PEMANDU), 2015, Solid Waste Management Lab 2015, Ministry of Housing and Local Government, Putrajaya, Malaysia.

Pressley, P.N., Levis, J.W., Damgaard, A., Barlaz, M.A., DeCarolis, J.F., 2015, Analysis of material recovery facilities for use in life-cycle assessment, Waste Management, 35, 307–317.

Silva, V., Contreras, F., Bortoleto, A.P., 2021, Life-cycle assessment of municipal solid waste management options: A case study of refuse derived fuel production in the city of Brasilia, Brazil, Journal of Cleaner Production, 279, 123696.

Woon, K.S., Lo, I.M.C., 2013, Greenhouse gas accounting of the proposed landfill extension and advanced incineration facility for municipal solid waste management in Hong Kong, Science of The Total Environment, 458–460, 499–507.

Woon, K.S., Phuang, Z.X., Lin, Z., Lee, C.T., 2021, A novel food waste management framework combining optical sorting system and anaerobic digestion: A case study in Malaysia, Energy, 232, 121094.