ORIGINAL ARTICLE

Assessing the Impact of COVID-19 on Solid Waste Generation and Environmental Health Footprint: A Case Study

*Sharifah Norkhadijah Syed Ismail[1,2], Nurul Azwa Muhamad Tamrin[1], Emilia Zainal Abidin[1], Irniza Rasdi[1], Aida Soraya Shamsuddin[3], Nurulain Mustafa Udin[4]

[1] Department of Environmental and Occupational Health, Faculty of Medicine and Health Sciences, Universiti Putra Malaysia, 43400 Serdang, Selangor.
[2] Malaysian Research Institute on Ageing (MyAgeing), Universiti Putra Malaysia, 43400 Serdang, Selangor.
[3] Southeast Asia Disaster Prevention Research Initiative (SEADPRI), Institute for Environment and Development (LESTARI) LESTARI, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor
[4] Faculty of Applied Sciences, University Teknologi MARA, 40450 Shah Alam, Selangor Darul Ehsan

ABSTRACT

Introduction: The profound influence of the COVID-19 pandemic on diverse societal facets including the solid waste generation patterns in Malaysia. **Methods:** The present research aims to evaluate the ramifications of the COVID-19 pandemic on the landscape of solid waste generation within Malaysia. By analyzing data sourced from waste management authorities, this study explores the shifts in waste generation patterns that unfolded during the pandemic phase, investigating their implications for the imperative goal of environmental sustainability. **Results:** Among the aggregate of solid waste generated, the highest composition was contributed by domestic waste (81%), followed by bulky and garden waste (13%), and public cleansing waste (6%). The total solid waste volume exhibited a diminishing trend preceding the pandemic, spanning from 3.4 million tonnes in 2014 to 3.1 million tonnes in 2019. However, in the pandemic during 2020, the volume underwent a further reduction to 2.9 million tonnes. A comparison of waste generation across quartiles pre-pandemic and during its course, a pronounced decline in Q2 (encompassing April to June), manifesting as a decrease from 783 thousand tonnes to 684 thousand tonnes. Meanwhile, no significant difference was observed across the remaining quartiles. The decrease in waste generation during the pandemic engendered a positive impact on curtailing estimated total direct emissions of methane (CH_4), carbon dioxide equivalent (CO_2-eq), and leachate in landfills, yielding a substantial health risk. **Conclusion:** In conclusion, this research provides valuable insights into the pandemic's impact on solid waste generation in Malaysia, informing vital future waste management strategies and policies.

Keywords: COVID-19; Solid waste management; Waste generation; Environmental impact; Health risk

Corresponding Author:
Sharifah Norkhadijah Syed Ismail, PhD
Email: norkhadijah@upm.edu.my
Tel: +603-97692857

INTRODUCTION

The COVID-19 pandemic has had profound global impacts on human lives (1), causing disruptions in various aspects including health, humanitarian efforts, economy, and societal activities. Malaysia, being one of the countries with a high number of COVID-19 cases and the highest number of confirmed cases in Southeast Asia as reported on April 11, 2020, was not exempt from these effects. To mitigate the spread of COVID-19, Malaysia implemented the Movement Control Order (MCO) during the pandemic, which involved the closure of non-essential businesses while essential services continued to operate (2).

The Solid Waste Management and Public Cleansing Corporation (SWCorp) in Malaysia has reported a notable increase in the volume of domestic waste generated, surpassing 200,000 tonnes each month since the commencement of the Movement Control Order (MCO) (3). Similar trends have been observed in other countries, such as North America, where the implementation of lockdown measures by authorities to contain the outbreak has led to potential changes in the volume and sources of solid waste (4). The surge in trash generation during the pandemic, particularly in household waste, can be attributed to the increased use of face masks, plastic packaging, various types of Personal Protective Equipment (PPE), and the disposal of hazardous items like batteries and empty chlorine bottles (5).

Moreover, individuals experienced a sense of panic, prompting them to take precautions against the disease by using personal protective equipment (PPE) and stockpiling food and essential items prior to the implementation of lockdown measures by the government. One contributing factor to this behavior was the concern about potential supply shortages (6). In response to lockdown or stay-at-home orders, households turned to online platforms to purchase food and other daily necessities. In Malaysia, popular food delivery services such as Food Panda, Grab, and Lalamove emerged as preferred alternatives, facilitating over two million deliveries between July and September 2020, as reported by Grab Malaysia (3). Similarly, countries like the United States witnessed an increase in online shopping, food delivery, and stockpiling of food and items, leading to potential waste from spoilage and excess packaging. These behaviors were driven by panic buying ahead of the announcement of lockdown measures as a preventive measure against COVID-19.

The significant increase in domestic waste during the pandemic, observed in many countries including Malaysia, poses substantial risks to both human health and the environment. This is primarily due to changes in waste composition generated by households during the enforcement of the Movement Control Order (MCO). In Malaysia, an analysis of landfill data in 2019 revealed that food waste accounted for the largest portion at 30%, followed by plastic at 24.8% (3). Solid waste has a profound impact on the environment and human health, mainly because waste generated and deposited in landfills release harmful gases such as methane and carbon dioxide. Methane, in particular, has 21 times the potency of carbon dioxide, making it highly hazardous (7). Landfilling, if chosen as the primary disposal option, leads to a 50% increase in greenhouse gas emissions, exacerbating environmental degradation (8). Moreover, as landfills approach their maximum capacity, space constraints become a critical issue.

Furthermore, leachate produced from landfill activities poses a potential risk to human health due to its content of organic matter, inorganic compounds, heavy metals, and organic xenobiotics (9). These compounds can be toxic and carcinogenic to humans. When leachate enters the soil and water, it not only harms ecosystems but also poses a threat to human health, as highlighted by Davoli et al., (10). Additionally, landfilling activities can contribute to the transmission of communicable diseases such as cholera, dysentery, dengue, diarrhea, and leptospirosis. Solid waste in landfills serves as a breeding ground for mosquitoes and a food source for rodents, flies, and insects, thus facilitating the spread of these diseases (11).

Limited studies have been conducted to assess the potential impact of the COVID-19 on Municipal Solid Waste (MSW) generation in Malaysia and its implications for environmental effects and health risks. Therefore, this study aims to provide valuable insights into the influence of COVID-19 pandemic on solid waste generation in Malaysia. It also seeks to examine the environmental impact and health risks associated with the generation of solid waste during this period. By addressing this research gap, this study contributes to a better understanding of the relationship between the COVID-19 pandemic, solid waste generation, environmental consequences, and health risks in Malaysia.

MATERIALS AND METHODS

The waste volume data for the analysis were obtained from the Domestic Waste and Public Cleansing Division of the Solid Waste and Public Cleansing Corporation (SWCorp), covering the period from 2014 to 2020. This study focuses on the states that have implemented the Solid Waste and Public Cleansing Management Act 2007 (Act 672), thereby determining the scope of the research. Act 672 is a specific law in Malaysia that focuses on solid waste management and public cleansing. This act is aimed at improving waste management practices, promoting recycling, and enhancing public cleanliness. The data set was collected from six states (Pahang, Perlis, Kedah, Negeri Sembilan, Malacca, and Johor) and two Federal Territories (Kuala Lumpur and Putrajaya), all under the management of SWCorp. Among these regions, Johor has the largest population, estimated at 3.76 million in 2018, followed by Kedah (2.17 million), Kuala Lumpur (1.78 million) and Pahang (1.67 million). Additionally, Kuala Lumpur has the highest Gross Domestic Product (GDP) per capita in 2019, amounting to MYR 233.33 million, followed by Johor (MYR 134 million/capita) and Pahang (MYR 58.3 million/capita) (12). The waste data sets encompass domestic waste, bulky and garden waste, and public cleansing waste.

The data was analyzed and organized using Microsoft Excel, categorizing it by states, years, and categories. To estimate the environmental impact (i.e. greenhouse gas (GHG) emissions and leachate production) and health risks (carcinogenic risk, and non-carcinogenic risk) from the Non-Methane Volatile Organic Compound (NMVOC) emissions, mathematical equations and formulas were employed within the Excel software (Table I). The default concentrations, unit risk factors (URF), and reference concentration (Rfc) of NMVOC were highlighted in Air Pollutant Emission Factors (AP-42, Vol.1, 1998) (15) and Unit risk factor (URF) for carcinogenic. (Integrated Risk Information System (17).

Table I : Summary of mathematical equations that were used to estimate the environmental impact and health risk analysis

Parameter	Mathematical Models	Source
Methane emission (CH4)	**∑(MSWTxMSWFxMCFxDOCxDOCFxF) 16/12** MSWT: Total municipal solid waste collected (tonne) MSWF: Municipal solid waste fraction (0.8 as Malaysia disposed 80% of waste to the landfills (Dong et al., 2010). MCF: Methane correction factor from 0.4 to 1.0 (Anwar, Saeed, Haslinda, Habib & Mat, 2012). DOCF: Degradable organic carbon fraction (0.77, Anwar et al., 2012) F: Value of fraction (0.5 where landfill approximately generates 50% of methane gases (IPCC, 2006)	(13)
Carbon dioxide equivalent (CO2-eq)	$\sum [CH_4 \times 25]$ CH_4: methane emission 25 as methane gases are 25 times GWP than CO_2 (IPCC, 2006).	(13)
Leachate production	$\sum [MSWT \times 0.21]$ MSWT: Total of municipal solid waste collected (tonne) Value of 0.21 is refers to one tonne of waste generates 0.21m^3 volume of leachate 1 x is the conversion of ppmv to m^3	(14)
NMVOC emissions	$\sum_P [1.82 \times TCH4 \times (\frac{CP}{10^6})]$ *P:* Type of NMVOC. Value of 1.82 is a multiplication factor as landfill generates 55% CH_4 and 45% of CO_2. TCH_4 : Total methane emission *CP:* concentration of compound *P.*	(15)
Inhalation exposure	∑i[Ci x IR x EF x ED])/(BW x AT) i : type of pollutant P (NMVOC) Ci: concentration of type i pollutant P emission IR: inhalation rate (15m^3/day for child; 23m^3/day for adult man and 21m^3/day for adult woman (Existing Default Values and Recommendations for Exposure Assessment A Nordic Exposure Group Project 2011, 2012). EF: exposure frequency which is 1 year (365 days). ED: exposure duration (the landfill lifespan - 20 years (SWML, 2015). BW: average body weight (Child: 31.8 kg; Adult man: 66.56kg; and Adult woman 58.44 (Mans et al., 2009). AT: averaging time for non carcinogenic effects is equal to the ED, and for carcinogenic effects, the AT is 72.7 year for male, and 77.6 year for female (DOSM, 2018)	(16)
Carcinogenic risk (Lifetime cancer risk, LCR)	IE: inhalation exposure to pollutant P (m^3/kg/year) URF: unit risk factor (URF) for carcinogenic that was obtained from the Integrated Risk Information System (IRIS), US EPA.	(16)
Non-carcinogenic risk (Hazard Quotient, HQ)	∑i (IE /Rfc) *i:* type of pollutant P (NMVOC). IE: inhalation exposure to pollutant P (m^3/kg/year) Rfc : Reference concentration (Table II)	(16)

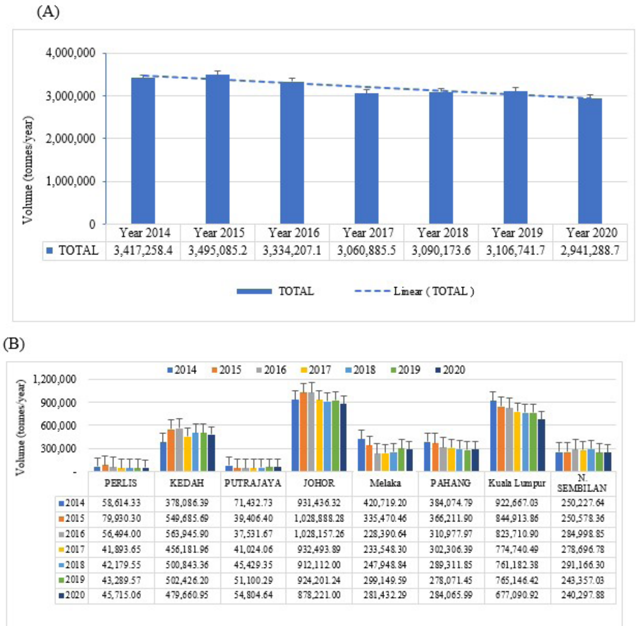

Figure 1 : The volume of solid waste (in tonnes) in Malaysia (A) and disaggregated by states (B) before the pandemic (from 2014 to 2019) and during the pandemic (2020).

RESULTS

Household waste constitutes the majority portion (81%) of Municipal Solid Waste (MSW), with bulky and garden waste accounting for 13%, and public cleansing waste contributing 6%. The total volume of solid waste generated exhibited a declining trend prior to the pandemic, ranging from 3.417 million tonnes in 2014 to 3.106 million tonnes in 2019. However, during the pandemic in 2020, the volume further decreased to 2.941 million tonnes (Fig 1a). Among the states, Johor, with the largest population, generated the highest waste volume, with a mean ± SD of 947,930.00 ± 58,032.03 tonnes per year, followed by Kuala Lumpur (795,636.00 ± 77,416.21 t/yr) and Kedah (490,118.64 ± 62,018.12 t/yr). Conversely, the lowest waste volumes were observed in Putrajaya (48,675.59 ± 11,835.83 t/yr) and Perlis (52,588.07 ± 13,877.91 t/yr) (Fig 1b).

To assess the impact of COVID-19 on waste generation, a comparison was made using data on waste volume by quarter years (Q1 to Q4) from 2019, representing the pre-pandemic situation, and 2020, representing the pandemic period. The results revealed that during the pandemic, the MSW volume in Q1 (January to March) decreased to 745,158.52 tonnes compared to the pre-pandemic volume of 768,843.91 tonnes. A similar trend was observed for Q2 (April to June) and Q3 (July to September). In Q2, the volume of waste generated during the pandemic was 684,592.50 tonnes, while before the pandemic, it was 783,163.51 tonnes. Similarly, in

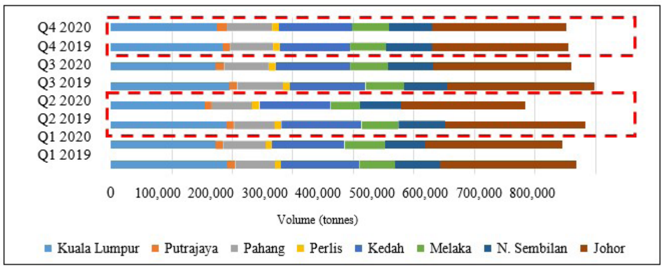

Figure 2 : The comparison of solid waste generation (in tonnes) before and during the pandemic, analyzed by quarter years.

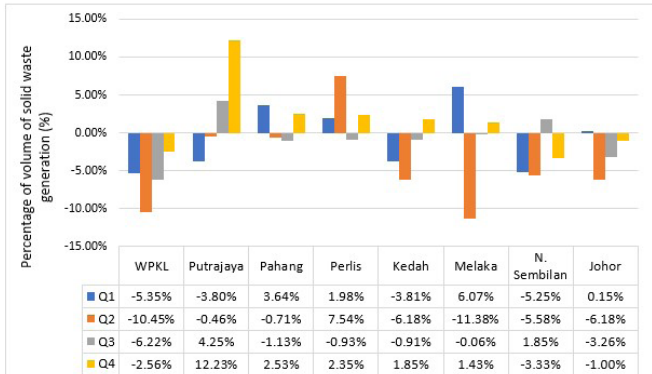

Figure 3 : The percentage reduction of solid waste generation during the pandemic, analyzed by quarter years.

Q3, the volume of waste generated during the pandemic was 759,727.31 tonnes compared to 798,371.35 tonnes before the pandemic. On the other hand, the volume of waste generation in Q4 (October to December) did not show a significant difference, with 756,363.01 tonnes before the pandemic and 751,810.40 tonnes during the pandemic (Figure 2). The Paired t-test analysis indicated a significant difference in terms of the volume of waste generated before and during the pandemic for Q2 ($t=2.565$, $p=0.037$).

The percentage of solid waste reduction during the pandemic for each quartile is highlighted in Figure 3. Kuala Lumpur consistently showed a reduction in waste volume across all quartiles, with the highest reduction recorded in Q2 (-10.45%). Melaka also experienced a significant reduction in solid waste of -11.38% in Q2. On the other hand, other states exhibited a fluctuating trend of waste reduction, with some quartiles showing an increasing trend. This can be observed in Putrajaya, where a substantial increase of 12.23% in waste generation was recorded in Q4. Similar trends were observed in Perlis, with a 7.54% increase in waste during Q2, and Melaka, with a 6.07% increase in Q1. A significant reduction was observed during Q2 with a range of reduction of 0.46%

to -11.38%. Observations on waste generation during the different phases of the movement control order indicate that the highest volume of waste (88,578.52 tonnes) was recorded during Phase 4 in June, while the lowest volume (194,428.42 tonnes) was recorded during Phase 2 in April.

The declining trend of waste generation during the pandemic had a significant impact on the estimated total direct emissions of methane (CH_4), carbon dioxide equivalent (CO_2-eq), and leachate in landfills, resulting in a substantial reduction. During the pandemic, significant reductions were observed in the amount of methane emitted, with levels decreasing from 110,805.67 tonnes to 104,904.59 tonnes. Additionally, the CO_2 equivalent (CO_2-eq) emissions decreased from 2,770,141.71 tonnes to 2,622,614.67 tonnes. Moreover, the volume of leachate decreased from 536,571.87 m3/yr to 507,996.13 m3/yr during the same period.

The twenty-one compounds of NMVOC were selected and assessed for non-carcinogenic risk based on the existing reference concentration for inhalation exposure (Rfc) data. A Hazard Index (HI) greater than 1 (HI > 1) indicates a non-carcinogenic risk to human health. The analysis revealed that HI values within acceptable limits for both prior and during the pandemic, suggesting a non-carcinogenic health risk. Additionally, eight compounds from the halogenated category were selected and assessed for carcinogenic risk using unit risk factor (URF) data. A Lifetime Cancer Risk (LCR) exceeding 1.0E-04 and 1.0E-03 indicates a carcinogenic risk to human health. The analysis indicated that the LCR values were within acceptable limits.

DISCUSSION

The study revealed a decreasing trend in solid waste generation in Malaysia between 2014 and 2020. According to Uding Rangga et al., the enforcement of Act 672 in 2007 led to a decline in the volume of domestic waste landfilled, from the implementation of a waste segregation scheme. Furthermore, the waste segregation program, introduced in 2015, effectively encouraged households to participate in source separation, resulting in a reduction in overall waste generation (18).

Furthermore, the results indicate that domestic waste volume is significantly higher compared to other waste types. This is primarily because domestic waste constitutes the largest proportion of total waste produced in Malaysia, as observed in other developed countries such as Singapore, Germany, and Austria (18-20). In Malaysia, domestic waste accounts for over 90% of the total waste dumped in landfills (21), with households being the main contributors to domestic waste generation. Approximately 80% to 90% of domestic waste is sent to landfills for disposal (21). Notably, Johor and Kuala Lumpur are the top waste producers in the country, while Perlis generates the least amount of solid waste. This can be attributed to the population size, as Johor (3.76 million in 2019) and Kuala Lumpur (7.78 million in 2019) have higher populations. Household waste constitutes the primary component of Municipal Solid Waste (MSW) in Malaysia, with commercial and institutional waste following closely behind. The sources of MSW in Malaysia exhibit variations based on the size of cities and the economic conditions prevailing in each local authority area (22). Factors such as urbanization, economic development, and population growth have an influence on the total waste volume produced in these areas (23). Additionally, according to DOSM (24), Johor and Kuala Lumpur contributed 72.3% of Malaysia's total Gross Domestic Product (GDP) per capita in 2019, further emphasizing their significant role among the six contributing states.

Overall, the study revealed a significant reduction in the volume of waste generated during Quarter 2 (Q2) of the pandemic. These findings suggest that the implementation of lockdown measures and travel restrictions had a substantial impact. According to SWCorp, the total volume of solid waste sent to landfills has decreased by 30%, despite an increase in domestic waste volume in Johor, attributed to people staying at home and practicing waste separation at the source (25). Furthermore, this drop can be attributed to the government's directive to close non-essential business premises, resulting in a lack of contribution from commercial, industrial, and institutional waste. It is worth mentioning that the increase in domestic waste did not surpass the rise in waste generated by the commercial, industrial, and institutional sectors. Some landfill operators have reported a decrease of 10% to 30% per day in the volume of waste entering their landfills since the adoption of the lockdown measures in Malaysia (26).

As the pandemic subsides and societies adapt to the new normal, waste generation patterns may continue to evolve. Some potential post-pandemic waste generation patterns could include the continued medical waste (27). The rise in e-commerce during the pandemic may continue to influence waste patterns, with an increase in packaging waste as more people shop online (28). With the remote work remains prevalent during post-pandemic, there might be sustained changes in waste patterns related to home offices, such as increased paper and electronic waste (29).

Furthermore, people's increased awareness of hygiene and waste management during the pandemic could lead to more responsible waste disposal habits. On the positive side, there could be a greater emphasis on sustainable practices, such as reducing single-use items and promoting circular economy initiatives. Governments and local authorities might adjust waste management strategies based on post-pandemic waste patterns, focusing on areas that require more attention. Understanding these patterns is crucial for effective waste management, resource allocation, and environmental sustainability efforts (29).

The implementation of lockdown measures alone was insufficient to offset the increase in domestic waste, despite the significant reduction in waste generated from economic activities in most cities. Naughton explained in their study that the volume and composition of waste during the pandemic varied across different areas (27). Additionally, the composition of municipal solid waste (MSW) is heterogeneous within each community and is influenced by factors such as income level, lifestyle, climate, household type, affluence, and region (5). For instance, in Hubei Province, China, the quantity of MSW generated in large and medium cities decreased by 30%, while the output of medical waste increased by over 370% (5, 28).

Moreover, the COVID-19 pandemic has been associated with a surge in plastic packaging waste, particularly from personal protective equipment (PPE), in addition to food waste (29). In Singapore, during the two-month circuit breaker period of stay-at-home curbs, an additional 1,334 tonnes of plastic garbage, equivalent to the weight of 92 double-decker buses, was generated from takeaway and delivery meals (30). These examples highlight the complex dynamics of waste generation during the pandemic, with various factors influencing the types and quantities of waste produced in different regions.

Furthermore, a recent research study conducted by Tan and Siti Najihah (31) revealed that the percentage of Malaysians in Penang who preferred to shop for groceries "1-2 times each week" decreased from 68% to 66% during the movement control order (MCO), which mandated individuals to only shop when necessary. The MCO also implemented other strict measures such as the prohibition of buffet activities at hotels and the replacement of dine-in services with only takeaways. These measures likely contributed to the reduction in solid waste during Quarter 2 (Q2). The temporary shutdown of hotel buffets, for instance, led to a decline in solid waste generated by the commercial sector. This trend was observed in other countries as well, such as the United States, where hotel buffets were temporarily closed due to safety concerns and may not reopen even after the COVID-19 situation has improved (32).

In addition, Carvalho (33) reported that an initial survey conducted by The Malaysia Singapore Coffeeshop Proprietors' General Association (MSCPGA) and the Malaysian Muslim Restaurant Owners Association (Presma) indicated that over 2,000 coffee shops and mamak restaurants in the country have permanently closed down, and 80% of their members have ceased business operations since the implementation of the lockdown measures. These closures have also contributed to the reduction in waste generation during the pandemic.

Although the results indicate no significant difference in the volume of solid waste generated between Quarter 3 (Q3) and Quarter 4 (Q4), it is important to note that the volume of solid waste generated increased compared to Q2. This increase can be attributed to the lifting of restrictions during this period, allowing for more flexibility and permitted activities. As business operations and economic sectors started to reopen, they contributed to the overall waste generated.

For instance, the federal government of Malaysia agreed to remove limitations on eateries, hawkers, and markets, and extended the Conditional Movement Control Order (MCO) until June 9, 2020, enabling all eateries, including food delivery services, to operate until 10 pm (34). This relaxation of restrictions played a role in the higher waste generation observed during Q3 and Q4.

The comparison of estimated GHG direct emissions before and during the pandemic showed a significant decrease. This reduction can be attributed to the decrease in the total amount of solid waste collected during the pandemic and a decrease in waste being sent to landfills. Disposal of solid waste in landfills contributes to a significant amount of GHG emissions through the process of bacterial decomposition (35). Microorganisms naturally present in the garbage and the soil used to cover the landfill break down organic waste, leading to the release of GHGs.

Recent reports from the United Nations Environment Programme (UNEP) have warned of increasing GHG emissions at an average rate of 1.4 percent per year since 2010. However, the COVID-19 pandemic is expected to result in a 7% reduction in emissions in 2020 compared to 2019 levels (36). Additionally, a study by Naderipour et al., (37) reported a reduction in GHG emissions during the implementation of the MCO in Malaysia, with emissions decreasing from 8 Mt CO_2eq to <1 Mt CO_2eq from January to May 2020. Indonesia has also experienced a similar trend, with the global warming potential from waste output dramatically decreasing from 1,859.6 kg

CO_2eq/day to 420.8 kg CO_2eq/day before and during the pandemic (38).

This study also observed a significant decrease in leachate production before and during the pandemic. As the estimation was based on the volume of waste disposed of in landfills, the reduction in total waste collected resulted in a reduction in the estimated volume of leachate production. Although there is no direct correlation between high solid waste dumped in landfills and the volume of leachate production, it is generally assumed that leachate volume increases with the increase in waste volume. Other factors such as intensive precipitation, landfill age, waste composition, and moisture content also influence leachate production (18, 39, 40).

According to Bernama (25), the domestic sector accounts for 44.5% of the 16,667.5 tonnes of food waste generated daily in Malaysia, as reported by SWCorp Malaysia. Despite the decrease in waste sent to landfills during the pandemic, the high organic composition and moisture content of food waste from domestic sources in Malaysia can still contribute to significant leachate production in landfills. Leachate problems have previously occurred in six solid waste landfills in Malaysia (41). Moreover, leachate poses a risk to human health by polluting drinking water sources with heavy metals, including Chromium, Cadmium, Lead, Mercury, Nickel, Copper, Zinc, Iron, and Selenium (42).

In this study, the emissions of all non-methane volatile organic compounds (NMVOCs) were found to be low during the pandemic, which is consistent with the reduction in waste volume. The study assessed the health risks for non-carcinogenic and carcinogenic effects before and during the pandemic among different study groups, including adults (both men and women) and children, and found them to be within acceptable levels. Typically, the decomposition process of waste in landfills produces NMVOCs at levels less than 1% (43).

Another study conducted by Carriero et al., (44) in Naples and Campania, Italy, which involved seven landfills in the Giugliano municipality, also reported acceptable health risks associated with NMVOC exposure. These landfills received a mixture of toxic waste from industries, hospitals, and urban sources. The study concluded that the concentrations of VOC compounds simulated in nearby cities were below the threshold limits for acute and chronic diseases, suggesting that fugitive emissions from the landfills did not pose a severe threat to human health.

It should be noted that high concentrations of NMVOCs released from landfills can occur when solid waste is not pre-treated prior to deposition (45). Therefore, despite the findings of this study, it is still essential to estimate the emissions of NMVOCs in landfills. This is because NMVOCs emitted from landfills can contain toxic and odorous gases that may pose health problems to the general public. Furthermore, exposure to aromatic VOCs such as benzene, toluene, and 1,3-butadiene can be potentially hazardous, as high levels of exposure to these compounds can affect human health (46, 47).

CONCLUSION

In conclusion, the COVID-19 pandemic has had a significant impact on the generation of Municipal Solid Waste (MSW) in the country, leading to a notable decrease in waste volume throughout the year. The findings of our study demonstrate a clear reduction in solid waste generation during the movement control order, which can be attributed to various factors such as business closures, travel restrictions, waste segregation programs, and the adoption of new norms. The decrease in waste volume sent to landfills has not only contributed to a significant reduction in greenhouse gas (GHG) emissions but has also resulted in a noticeable decrease in leachate production and levels of non-methane volatile organic compounds (NMVOCs). This highlights the positive environmental impact of reducing solid waste generation and emphasizes the importance of sustainable solid waste management practices. The waste reduction trend observed during the Movement Control Order (MCO) depends on various factors, including societal behaviors, government policies, economic conditions, and environmental awareness. While it's challenging to predict with certainty, there are strategies that can contribute to sustaining the waste reduction trend. This includes the continued efforts to promote and educate the public about sustainable waste management practices can help maintain awareness. Encouraging behaviors such as reducing single-use plastics, practicing responsible disposal, and recycling can make a significant difference. Governments can play a crucial role by implementing and enforcing waste reduction policies and regulations. These could include measures like extended producer responsibility (EPR) programs, plastic bans, and incentives for businesses to adopt sustainable packaging. It's important to note that maintaining a sustained waste reduction trend will require a multifaceted approach involving individuals, businesses, communities, and governments working together. Continuous monitoring, evaluation, and adaptation of strategies based on changing circumstances will be essential for long-term success.

Furthermore, our study indicates that the exposure to NMVOCs falls within an acceptable range of health risks. This suggests that the measures taken to reduce waste volume during the pandemic have helped maintain a safe level of exposure for the general public. Based on these findings, it is crucial to develop a long-term plan for sustainable solid waste management in Malaysia. This plan should include initiatives to increase public awareness and engagement to effectively control and reduce solid waste generation. By implementing comprehensive waste management strategies and promoting responsible waste disposal practices, we can achieve a more sustainable and environmentally friendly approach to waste management in the country.

ACKNOWLEDGMENT

The authors would like to thank the Solid Waste Public Cleansing and Waste Management (SWCorp) Malaysia and Department of Environmental and Occupational Health, UPM as for their contribution and approval for this study to be conducted.

REFERENCES

1. Rume, T., & Islam, S. M. D. U. (2020). Environmental effects of COVID-19 pandemic and potential strategies of sustaina- bility. In Heliyon (Vol. 6, Issue 9). https://doi.org/10.1016/j.heliyon.2020.e04965
2. Tang, Kuok Ho Daniel. (2020). "Movement Control as an Effective Measure against Covid-19 Spread in Malaysia: An Over- view." Journal of Public Health (Germany). doi: 10.1007/s10389-020-01316-w
3. Rahim, R. (2021, March 11). Piles of waste, we want not. The Star. Retrieved from https://www.thestar.com.my/news/nation/2021/03/11/piles-of-waste-we-want-not
4. Kulkarni, B. N., & Anantharama, V. (2020). Repercussions of COVID-19 pandemic on municipal solid waste management: Challenges and opportunities. Science of the Total Environment, 743(2020), 140693. https://doi.org/10.1016/j.scitotenv.2020.140693
5. Das, A. K., Islam, Md. N., Billah, Md. M., & Sarker, A. (2021). COVID-19 and municipal solid waste (MSW) management: a review. Environmental Science and Pollution Research, 28(23), 28993–29008. doi:10.1007/s11356-021-13914-6
6. Manning-Schaffel, V. (2020, March 5). Coronavirus fears have emptied supermarket shelves. Are you panic-buying? Retrieved from NBC News website: https://www.nbcnews.com/better/lifestyle/coronavirus-fears-have-emptied-supermarket-shelves-are-you-panic-buying-ncna1148536
7. Karim Ghani, W.A.W.A., Rusli, I.F., Biak, D.R.A. and Idris, A. (2013), "An application of the theory of planned behaviour to study the influencing factors of participation in source separation of food waste", Waste Management, Vol. 33 No. 5, pp. 1276-1281
8. Lee, U., Han, J., Wang, M. (2017). Evaluation of landfill gas emissions from municipal solid waste landfills for the life-cycle analysis of waste-to-energy pathways, J. Clean. Prod., Vol. 166, pp. 335-342.
9. Christensen, T. H., Kjeldsen, P., Bjerg, P. L., Jensen, D. L., Christensen, J. B., Baun, A., Albrechtsen, H. J., Heron, G. (2001). Biogeochemistry of landfill leachate plumes, Applied Geochemistry, Vol. 16 (7–8), pp 659-718, https://doi.org/10.1016/S0883-2927(00)00082-2.
10. Davoli, E., Fattore, E., Paiano, V., Colombo, A., Palmiotto, M., Rossi, A.N., Grande, M. Il., Fanelli, R. (2010). Waste management health risk assessment: A case study of a solid waste landfill in South Italy,Waste Management, Vol. 30 (8–9); pp 1608-1613, https://doi.org/10.1016/j.wasman.2009.10.013.
11. Nor Faiza, M.T, Noor Artika, H., Mohammad Farhan, R, Edre, M.A, Rus, R.M. (2019). Solid Waste: Its Implication for Health and Risk of Vector Borne Diseases. Journal of Wastes and Biomass Management (JWBM), Vol.1 (2); pp 14-17.
12. Department of Statistics Malaysia. (2019). GDP by State, 2010-2016. Retrieved from https://www.dosm.gov.my
13. Intergovernmental Panel on Climate Change (IPCC), (2006) "Waste," in IPCC Guidelines for National Greenhouse Gas Inventories, S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe, (Ed) Hayama, Kanagawa: Institute for Global Environmental Strategies (IGES), Japan.
14. Ministry of Housing and Local Government (KPKT). (2015). Solid Waste Management Lab 2015. Retrieved from http://www.kpkt.gov.my/resources/index/user_1/Attachments/hebahan_slider/sl aid_dapatan_makmal.pdf.
15. United States Environmental Protection Agency (U.S. EPA) (1998) AP 42, Fifth Edition Compilation of Air Pollutant Emissions Factors, Volume 1: Stationary Point and Area Sources. In Chapter 2: Solid Waste Disposal 1-19.
16. United States Environmental Protection Agency (US EPA), (2011) Exposure Factors handbook: 2011 Edition, vol. EPA/600/R-, no
17. US EPA. (2018, August 23). Human Health Risk Assessment. Retrieved from US EPA website: https://www.epa.gov/risk/human-health-risk-assessment.
18. Uding Rangga, J., Syed Ismail, S. K., Rasdi, I., Karuppiah, K., & Ikmal Irozi, M. (2019). Environmental Impact, Health Risk, and Management Cost of Landfilling Practice: A Case Study in Klang, Selangor, Malaysia. Scholarena, 2(1), 1–12.
19. Pickin, J., Randell, P., Trinh, J., & Grant, B. (2018). National Waste Report 2018. Department of the Environmental and Energy; Blue Environment Pty Ltd.
20. Jaron, A., & Kossmann, C. (2018). Waste management in Germany 2018. Federal Ministry for the Environment, NatureCon- servative and

Nuclear Safety (BMU).
21. National Solid Waste Management Department (2013). Survey on Solid Waste Composition , Characteristics & Existing Practice of Solid Waste Recycling in Ma- laysia. Putrajaya. Retrieved from http://jpspn.kpkt.gov.my/resources/index/user_1/Sumber_Rujukan/kajian/Final_ Re- port_REVz.pdf
22. Samsudin, M. D. M., & Mat Don, M. (2013). Municipal Solid Waste Management in Malaysia: Current Practices, Challenges and Prospects. ResearchGate, 62(1), 95–101. https://doi.org/10.11113\/jt.v62.1293
23. Hoornweg D, Perinaz BT (2012) What a Waste: A Global Review of Solid Waste. Retrieved from https://www.thestar.com.my/news/nation/2020/03/25/theres-enough-bread-to
24. Department of Statistics Malaysia Official Portal. (2021). Retrieved from https://www.dosm.gov.my/v1/index.php?r=column/cthemeByCat&cat=102
25. Bernama. (2020, October 20). SWCorp: Food waste drops during MCO, rises again soon after. https://www.nst.com.my/news/nation/2020/10/633738/swcorp-food-waste-drops-during-mco-rises-again-soon- after
26. Teoh, M. (2020, April 22). Blue skies, less waste: Covid-19 and the MCO's effects on the environment l The Star Online. Retrieved from www.thestar.com.my website: https://www.thestar.com.my/lifestyle/living/2020/04/22/earth-day-a-wake-up-call-to-lead-more-environmentally-sustainable-lives
27. Jindal, A. K., Sar, S. K. (2023). Medical waste management during COVID-19 situation in India: Perspective towards safe environment. Waste Management Bulletin. Vol (1): 1, Pages 1-3, https://doi.org/10.1016/j.wmb.2023.03.002.
28. Peula, F.J., Martнn-Lara, M.Б. & Calero, M. (2023) Effect of COVID-19 pandemic on municipal solid waste generation: a case study in Granada city (Spain). J Mater Cycles Waste Manag 25, 2543–2555 (2023). https://doi.org/10.1007/s10163-023-01671-2
29. Wang, Q., Zhang, C. & Li, R. (2023). Plastic pollution induced by the COVID-19: Environmental challenges and outlook. Environ Sci Pollut Res 30, 40405–40426 (2023). https://doi.org/10.1007/s11356-022-24901-w
30. Navene E. (2020, June 5). Singapore households generated additional 1,334 tonnes of plastic waste during circuit breaker: Study. Today. Retrieved from; https://www.todayonline.com/singapore/singapore-households-generated-additional-1334-tonnes-plastic-waste-during-circuit-breaker#:~:text=Navene%20Elangovan&text=Twitter%20Email%20LinkedIn-,SINGAPORE%20—%20An%20extra%201%2C334%20tonnes%20of%20plastic%20waste%2C%20equivalent%20to,curbs%2C%20a%20survey%20has%20found.
31. Tan T., Siti Najihah C. S. (2020). The Impacts of Movement Control Order (MCO) Towards Waste Generation in Penang Island. Penang Green Council. https://www.pgc.com.my/2020/wp-content/uploads/2020/10/The-Impacts-of-Movement-Control-MCO-Towards-Waste-Generation-in-Penang-Island.pdf
32. Shapoval V, HΔgglund P, Pizam A, Abraham V, CarlbΔck M, Nygren T, Smith RM (2020). The COVID-19 pandemic effects on the hospitality industry using social systems theory: A multi-country comparison. Int J Hosp Manag. 2021 Apr;94:102813. doi: 10.1016/j.ijhm.2020.102813. Epub 2020 Dec 28. PMID: 34866741; PMCID: PMC8631802.
33. Carvalho, M. (2020, June 12). Over 2,000 coffee shops, eateries shut permanently. Retrieved from https://www.thestar.com.my/news/nation/2020/06/12/over-2000-coffee-shops-eateries-shut-permanently
34. Daim, N., & Harun, H.N (2021). Operation hours for eateries extended, effective tomorrow. https://www.nst.com.my/news/nation/2021/06/702769/operation-hours-eateries-extended-effective-tomorrow
35. Rena, R., Arya, S., Chavan, D., Aiman, S., & Kumar, S. (2020). Reducing Greenhouse Gas Emission From Waste Landfill. Encyclopedia of Renewable and Sustainable Materials, 685–701. https://doi.org/10.1016/b978-0-12-803581-8.11022-7
36. The Jakarta Post (2021, May 11). Reducing net-zero emissions key to climate action. https://www.thejakarta- post.com/adv/2021/05/11/reducing-net-zero-emissions-key-to-climate-action.html.
37. Naderipour, A., Abdul-Malek, Z., Ahmad, N.A., Kamyab, H., Ashokkumar, V., Ngamcharussrivichai, C., Chelliapan, S. (2020). Effect of COVID-19 virus on reducing GHG emission and increasing energy generated by renewable energy sources: A brief study in Malaysian context. Environmental Technology & Innovation, Vol. 20 (101151). https://doi.org/10.1016/j.eti.2020.101151
38. Suryawan, I. W., Rahman, A., Septiariva, I. Y., Suhardono, S., & Wijaya, I. M. (2020). Life Cycle Assessment Of Solid Waste Generation During And Before Pandemic Of Covid-19 In Bali Province. Journal of Sustainability Science and Manage- ment, 16(1), 11-21. doi:10.46754/jssm.2021.01.002
39. Aziz, H. A., Adlan, M. N., Amilin, K., Yusoff, M. S., Ramly, N. H., & Umar, M. (2012). Quantification of leachate generation rate from a semi-aerobic landfill in Malaysia. Environmental Engineering and Management Journal, 11(9), 1581–1585.
40. Maiti, S. K., De, S., Hazra, T., Debsarkar, A., & Dutta, A. (2016). Characterization of Leachate and Its Impact on Surface and Groundwater Quality of a Closed Dumpsite - A Case Study at Dhapa,

Kolkata, India. In Interna- tional Conference on Solid Waste Management, 5IconSWM 2015 (Vol. 35, pp. 391–399).
41. Malay Mail (2017, Jul 8). Six solid waste landfills have serious leachate contaminant issues, says Wan Junaidi. Retrieved from; https://www.malaymail.com/news/malaysia/2017/07/08/six-solid-waste-landfills-have-serious-leachate-contaminant-issues-says-wan/1416565
42. Urase, T., Salequzzaman, M., Kobayashi, S., Matsuo, T., Yamamoto, K., & Suzuki, N. (1997). Effect of high concentration of organic and inorganic matters in landfill leachate on the treatment of heavy metals in very low concentration level. Water Science and Technology, 36(12), 349–356. https://doi.org/10.1016/s0273-1223(97)00723-3
43. Tassi F, Montegrossi G, Vaselli O, Liccioli C, Moretti S, Nisi B. Degradation of C2-C15 volatile organic compounds in a landfill cover soil. Sci Total Environ. 2009 Jul 15;407(15):4513-25. doi: 10.1016/j.scitotenv.2009.04.022. Epub 2009 May 14. PMID: 19446310.
44. Carriero, G., Neri, L., Famulari, D., Di Lonardo, S., Piscitelli, D., Manco, A., Esposito, A., Chirico, A., Facini, O., Finardi, S., Tinarelli, G., Prandi, R., Zaldei, A., Vagnoli, C., Toscano, P., Magliulo, V., Ciccioli, P. & Baraldi, R. (2018). Composition and emission of VOC from biogas produced by illegally managed waste landfills in Giugliano (Campania, Italy) and potential impact on the local population. Science of the Total Environment, 640-641(2018), 377–386. doi:10.1016/j.scitotenv.2018.05.318
45. Pawłowska, M., Czerwiński, J., & Stępniewski, W. (2008). Variability of the non-methane volatile organic compounds (NMVOC) composition in biogas from sorted and unsorted landfill material. Archives of Environmental Protection, Vol. 34(no. 3), 287–298. Retrieved from http://yadda.icm.edu.pl/baztech/element/bwmeta1.element.baztech-article-BUS5-0013-0048 planned behaviour to study the influencing factors of participation in source separation of food waste”,
46. Na, K., Kim, Y. P., & Moon, K. C. (2003). Diurnal characteristics of volatile organic compounds in the Seoul atmosphere. Atmospheric Environment, 37(6), 733–742. https://doi.org/10.1016/s1352-2310(02)00956-1
47. Fang, L., Norris, C., Johnson, K., Małgorzata, & Czerwinski. (2019). Toxic volatile organic compounds in 20 homes in Shanghai: Concentrations, inhalation health risks, and the impacts of household air cleaning. Building and Environment, 157, 309–318. doi:10.1016/j.buildenv.2019.04.047