ปริมาณการปล่อยก๊าซเรือนกระจกจากการจัดการขยะมูลฝอยของเทศบาลนครมัณฑะเลย์และทางเลือกในการลดก๊าซเรือนกระจก

Greenhouse gas emission from solid waste management of Mandalay municipality and possible mitigation options

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Received: 29 August 2022 ; **Revised**: 13 January 2023 ; **Accepted**: 16 February 2023

บทคัดย่อ

งานวิจัยฉบับนี้ ศึกษาวิเคราะห์องค์ประกอบของขยะมูลฝอยชุมชน ศักยภาพทางด้านพลังงาน และผลคาดการณ์ปริมาณการปล่อยก๊าซเรือนกระจกจากการจัดการขยะทั้งในปัจจุบันและภาพฉายในอนาคต ของเมืองมัณฑะเลย์ สาธารณรัฐแห่งสหภาพเมียนมาร์ การสุ่มตัวอย่างขยะดำเนินการในเดือนมีนาคม ปี 2562 ที่สถานีรวบรวมและขนส่งขยะ 2 แห่งของเมือง พบว่า ขยะจากสวนมีปริมาณร้อยละ 45.4 ของน้ำหนักขยะเปียก ในขณะที่ขยะพลาสติก ขยะอาหาร และขยะสิ่งทอคิดเป็นร้อยละ 15.4, 14.4 และ 11.0 ตามลำดับ ที่เหลือ (ร้อยละ 13.7) ประกอบด้วยเศษไม้ ยาง หนัง กระดาษ ผ้าอ้อม โลหะ และแก้ว ความชื้นของตัวอย่างขยะมีค่าร้อยละ 43.2 ด้วยข้อมูลองค์ประกอบขยะดังกล่าว ศักยภาพทางด้านพลังงานจากขยะมูลฝอยของเมืองมีค่าประมาณ 2,357 เทระจูลล์ เทียบเท่าศักยภาพการผลิตไฟฟ้า 5.2-10.3 เมกะวัตต์ ภายใต้สมมติฐานที่กำหนดให้โรงไฟฟ้าขยะมูลฝอยมีประสิทธิภาพ 10-20% และเดินระบบ 300 วันต่อปี การประเมินปริมาณการปล่อยก๊าซเรือนกระจกจากการจัดการขยะด้วยวิธีการตาม 2006 IPCC guidelines for national GHG inventories พบว่ามีค่าเท่ากับ 94 Gg CO_2-eq ในปี 2562 ปริมาณการเกิดขยะมูลฝอยในอนาคตจนถึงปี 2573 คาดการณ์โดยการใช้ univariate Grey model (GM (1,1)) ผลการศึกษาพบว่า ภายใต้การดำเนินธุรกิจตามปกติ ปริมาณก๊าซเรือนกระจกจะเพิ่มขึ้นอย่างต่อเนื่องจนถึง 820 Gg CO_2-eq ในปี 2573 งานวิจัยนี้ได้นำเสนอทางเลือกในการจัดการขยะมูลฝอย 2 ภาพฉายที่จะช่วยลดปริมาณการปล่อยก๊าซเรือนกระจกได้ โดยภาพฉายที่ 1 คือกรณีที่ประสิทธิภาพการเก็บขยะ และการนำกลับมาใช้ใหม่ดียิ่งขึ้น มีการใช้งานระบบหมักปุ๋ย และระบบหมักก๊าซชีวภาพ และภาพฉายที่ 2 คือกรณีที่มีการนำวัสดุและพลังงานจากขยะกลับมาใช้ประโยชน์เพิ่มมากยิ่งขึ้น ด้วยการเพิ่มการนำกลับมาใช้ใหม่ การหมักปุ๋ย และหมักก๊าซชีวภาพ และการผลิตพลังงานด้วยโรงไฟฟ้าเตาเผาขยะ รวมถึงการเปลี่ยนหลุมฝังกลบทั้งหมดให้เป็นหลุมฝังกลบแบบกึ่งใช้อากาศ ผลการศึกษาแสดงให้เห็นว่า ในปี 2573 แนวทางที่ 1 และแนวทางที่ 2 สามารถลดการปล่อยก๊าซเรือนกระจกได้ 6% และ 55% ตามลำดับ เมื่อเทียบกับกรณีการดำเนินธุรกิจตามปกติ

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Abstract

This study investigated municipal solid waste (MSW) composition, energy potential, and estimates of greenhouse gas (GHG) emissions from the current MSW management practice and the future MSW management scenarios of Mandalay municipality, Republic of the Union of Myanmar. Waste sampling was performed in March 2019 for two transfer stations, with garden and park waste accounting for 45.4 % by wet weight of MSW. Plastic, food, and textile waste accounted for 15.4, 14.4 and 11.0 wt%, respectively. The rest (13.7 wt%) comprised small pieces of wood, rubber, leather, paper, nappies, metal, and glass. The moisture content of MSW samples was 43.2 wt%. Based on this composition, the energy potential from MSW was approximately 2,357 TJ. The equivalent electricity production potential ranged from 5.2-10.3 MW, assuming an overall power plant efficiency of 10-20% and 300 working days per year. The amount of GHG emission from MSW management was estimated, using 2006 IPCC guidelines for national GHG inventories, to be 94 Gg carbon dioxide equivalent (CO2-eq) in 2019. MSW generation up to 2030 was forecasted using the univariate Grey model (GM (1, 1)). Under a business-as-usual (BAU) scenario, the GHG emission will increase to 820 Gg CO_2-eq in 2030. This study proposed two alternative MSW management scenarios for GHG mitigation based on the Mandalay waste management strategy. The first scenario (S1) represented the case where waste collection efficiency and recycling were enhanced, and the composting and aerobic digestion facilities were operated. The second scenario (S2) described the case where additional material and energy recovery through reuse and recycling, composting, anaerobic digestion, and waste-to-energy power plant were implemented. S2 also included conversions of all landfills into semi-aerobic landfills. The results showed that in 2030, S1 and S2 could reduce GHG emissions by 6% and 55%, respectively, compared to the BAU.

Keywords: Greenhouse gas emission, waste composition, MSW generation forecasting, energy potential, Mandalay city

Introduction

Global greenhouse gas (GHG) emissions are increasing mainly due to human activities. Anthropogenic GHG emissions affect climate change, and as a result, GHG management has attracted researchers' interest since the early 1900s (Goldenfum, 2012; Hu *et al*., 2020; Kumar *et al*., 2019; Malahayati & Masui, 2019). Compared to 1850-1900, the global surface temperature is very likely to rise by 1.0-1.8°C during 2081-2100 under the most optimistic scenario with the very low GHG emission and could increase by 3.3-5.7°C under the very high GHG emission scenario (Allan *et al*., 2021). The Waste sector accounts for 3.2% of global emissions (Ritchie *et al*., 2020). The key GHG emission from the Waste sector is CH_4 emission from landfills, followed by CH_4 and N_2O emissions from wastewater treatment and, to a lesser extent, fossil-CO_2 emission from waste combustion (Bogner *et al*., 2007). According to the 6th assessment report of the Intergovernmental Panel on Climate Change (IPCC), the global warming potential (GWP) of CH_4 for a 100-year time horizon is estimated to be 27.2 for the non-fossil origin and 29.8 for fossil origin (Masson-Delmotte *et al*., 2021). Therefore, it is crucial to carefully plan, select, and utilize appropriate waste and wastewater treatment technologies to mitigate GHG emissions as much as possible.

Mandalay city is the second largest city in Myanmar and the commercial hub of the upper and central parts of Myanmar. The city has a population of 1,134,577 people, with 945,191 people living in the municipal area (83%) and 189,386 people living in the countryside (17%). The population density increased from 99 persons/km^2 in 1973 to 124 persons/km^2 in 1983 and 200 persons/km^2 in 2014 (MIP, 2015). As with the economy's growth, increasing population and urbanization rate, municipal solid waste (MSW) generation in Mandalay city increases. Currently, the Cleansing Department of Mandalay City Development Committee (MCDC) is responsible for the MSW management system, including the primary, secondary, and final disposal. The primary MSW collection includes door-to-door collection with bell ringing and loudspeaker announcements using labours, curbside collection, and collections from dedicated community spaces or waste collection areas. The secondary MSW collection occurs at the transfer stations. Finally, the collected MSW is sent to the city's disposal sites, which can be described as poorly managed anaerobic landfills.

Mandalay municipality comprises six townships covering a total land area of 314.7 square kilometres. These six townships are grouped into 97 wards for administrative and public service management purposes. In 2019, only 85% of the total area of Mandalay municipality was provided with MSW collection service. The amount of collected MSW measured at disposal sites in 2019 was 419,165 t/year or 1,148 t/day (H.Myo, MCDC, personal communication, March 14, 2019). As the MSW amount increases, a well-planned and sustainable waste management system is in need. The current MSW management system must be modified to accommodate the changes in waste in terms of its quantity and its composition (MCDC, 2017).

According to the Myanmar Energy Master Plan (Emmerton, 2015), the current energy supply in Myanmar primarily relies on hydropower, gas, coal, petroleum, and biomass. Energy demand is growing yearly with the increasing population and urbanization rate. For a modern MSW management system, waste-to-energy incineration (WtEI) is essential for reducing the mass and volume of initial bulk waste and mitigating GHG emissions (Ferreira *et al*., 2014; Quina *et al*., 2014). Waste incineration can reduce MSW by 80-85% in weight and 95-96% in volume (Nidoni, 2017). Additionally, energy from waste can reduce fossil fuel use and help supply the country's energy demand. It is interesting to evaluate the energy potential of MSW from Mandalay city, as this information will be helpful for the future planning of the MSW management system. Thermal properties of waste and its energy potential estimates are essential in considering whether WtEI technologies should be implemented in the city.

One of the environmental concerns arising from improper MSW treatment in developing countries is the GHG emissions from disposal sites. To estimate and manage the GHG emission from MSW management effectively, one should know the amount of MSW generation, its composition, and the characteristics of MSW treatment and disposal technology used in that site of interest. Information on GHG emissions from MSW treatment and disposal sites should be estimated and systematically curated. A sound MSW management system should allow for continuous waste tracking and waste statistics obtained. Accurate waste statistics and composition are vital to improving waste treatment facilities.

This study aims to provide the necessary information to improve Mandalay's MSW management system. Therefore, this study surveyed Mandalay's MSW composition, evaluated the MSW energy potential, and estimated the amount of GHG emissions from current and future MSW management scenarios.

Materials and Methods

Study sites

This study focused on MSW management of Mandalay municipality. Mandalay municipality is divided into two areas: northern and southern. The northern area includes Aung Myay Thar Zan, Chan Aye Thar Zan and Mahar Aung Myay. The southern area includes Chan Mya Tharsi, Pyigyi Tagon and Amarapura. Each area has one waste transfer station and one waste disposal site. Waste from each area is collected daily and gathered at the transfer station before it is sent to the waste disposal site dedicated to each area: Kyar Ni Kan for the northern area and Taung inn-Myauk inn for the southern area. A map of Mandalay municipality, the locations of waste transfer stations and disposal sites is shown in Figure 1.

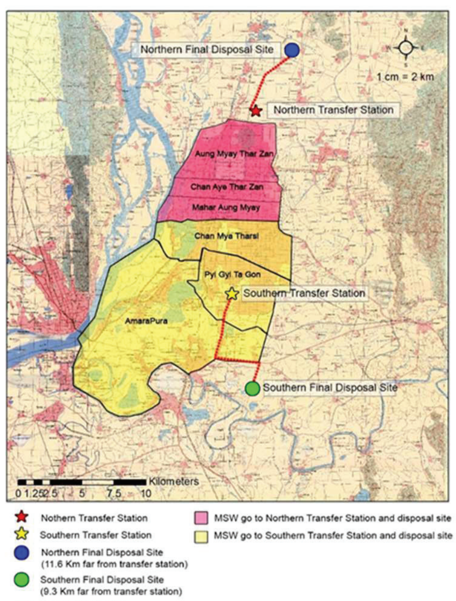


Figure 1 Study sites: Mandalay municipality boundary, locations of waste transfer stations and disposal sites (the base map was derived from survey Department Myanmar)

MSW composition analysis

MSW composition analysis was carried out at both transfer stations in March 2019. The working time was selected to be in March as it is in the dry season in Myanmar when the weather conditions are stable throughout the day. The waste sampling was designed to (1) include MSW from different areas across the Mandalay municipality and (2) cover both weekends and weekdays to ensure the representativeness of the data obtained.

For each transfer station, three waste samples were taken from three different sources (three trucks loaded with MSW from three different neighbourhoods) for composition analysis; one sample on a weekday and two samples on the weekend. In total, there were six samples representing the MSW from Mandalay municipality.

The method for MSW composition analysis was primarily referred to ASTM-D5231-92 (2016). Firstly, the collected MSW sample from the truck was thoroughly mixed, coned and quartered. Then, one quarter with a weight range of 91-136 kg is randomly selected to be hand-sorted. This study grouped MSW into 11 categories following the 2006 IPCC guidelines for national GHG inventories (Eggleston *et al*., 2006). Samples of MSW were analyzed for moisture content in a laboratory using a method described in ASTM-D3173/D3171-17a (2017).

Estimation of energy potentials

The calorific value (CV) of MSW is a crucial parameter in determining whether thermal waste treatment processes should be considered for a city. The gross calorific values (GCVs) and net calorific values (NCVs) of waste were reviewed and summarised in Table 1. This study selects the lowest and the highest GCVs from this literature review to estimate the range of energy content of Mandalay's MSW. In addition, the energy content was also calculated using the default NCVs given in the 2006 IPCC GL, volume 2: 10 TJ/Gg for a non-biomass fraction of municipal waste and 11.6 TJ/Gg for a biomass fraction of municipal waste (Eggleston *et al*., 2006).

The energy content of the total MSW was calculated by summing up the energy content of each waste component. The energy content of each waste component was calculated by multiplying the weight of that component with its respective CVs. Dry weights were used for the calculations based on GCVs, whereas wet weights were used for the calculations based on NCVs.

The wet weights of each waste component were calculated by multiplying the amount of MSW generation in 2019 with the results of waste composition analysis as shown in equation (1) :

$$W_{a,wet} = W_{msw,wet} \times \%C_a \qquad (1)$$

Where $W_{a,wet}$ is the wet weight of waste component a (kg), $W_{msw,wet}$ is the amount of MSW generation in Mandalay municipality (kg) in 2019 as reported by MCDC (2017), and %C is the percentage of waste component a (%) as reported by this study.

The dry weights of each waste component were calculated by using equation (2) :

$$W_{a,dry} = W_{a,wet} \times (1 - \%Moisture_a) \qquad (2)$$

Where $W_{a,dry}$ is the dry weight of waste component a (kg), $\%Moisture_a$ is the moisture content (%) for the waste component a. The $\%Moisture_a$ were based on the default moisture content values for each waste component suggested in the 2006 IPCC GL, volume 5 (Eggleston *et al*., 2006). These default values were then normalized by equation (3) to make the sum of moisture in all waste components equal to the total moisture content of MSW obtained from our laboratory analysis, $\%Moisture_{msw}$.

$$W_{msw,wet} \times \%Moisture_{msw} = \sum_{i=a}^{n}(W_{a,wet} \times \%Moisture_a) \qquad (3)$$

Where i = waste component a, b, c, … n

The energy potential of MSW (EP_{msw}) was estimated using equation (4) (Anshar *et al*., 2014).

$$EP_{msw} = W_{msw} \text{ x } CV_{msw} \qquad (4)$$

Where EP_{msw} is the energy potential from MSW (MJ), W_{msw} is the weight of MSW (kg), CV_{msw} is the net calorific value of the MSW (MJ/kg). The electricity production potential from WtEI in megawatts (MW) was estimated by referring to the average data of Thailand for the overall power plant efficiency of 10-20% with 300 working days per year (Phongphiphat *et al.*, 2022).

Table 1 Gross calorific values (GCVs) and net calorific values (NCVs) of waste reported by previous studies

References	Origin	Gross Calorific values (MJ/kg)						
		food waste	garden waste	Paper & cardboard waste	Wood waste	plastic waste	rubber &leather waste	textile waste
Menikpura & Basnayake (2009)	Sri lanka	18.40	15.80	15.00	14.20	33.30	23.00	17.00
Komilis *et al.* (2012)	Greece	20.93	17.20	15.93		39.35		
Franjo Franjo *et al.*, (1992)	Spain			16.02 ± 0.194		32.03 ± 0.397		23.16 ± 0.185
		Net Calorific values (MJ/kg)						
		Biomass fraction				Non-biomass Fraction		
Eggleston *et al.* (2006)	2006 IPCC GL	10.00				11.60		

Forecasting MSW generation and model verification

There are several methods for MSW generation forecasting, including descriptive statistical methods, time series analyses, regression analyses, and artificial intelligence models. All modelling approaches have their strengths and weakness. When this study was conducted, the available time series data for MSW generation in Mandalay were only from 2012-2019 (n = 8). Selecting a forecasting model that could work well with limited data was inevitable. Hence, this study utilized the univariate grey model, GM (1,1), as it requires a small number of samples or restricted data to conduct the forecasting (Wang *et al.*, 2018). The GM (1,1) is a one-variable grey differential equation model without considering influencing factors. The first-order differential equation of GM (1,1) is defined in equation (5) (Huang, 2012; Xu *et al.*, 2013) :

$$\frac{dx^{(1)}(t)}{dt} + ax^{(1)}(t) = b \tag{5}$$

The solution formula of the first-order differential equation is written as shown in equation (6) (Liu & Forrest, 2010).

$$x_1^{(0)}(k) = \left[x_1^{(0)}(1) - \frac{b}{a}\right](1 - e^{a})e^{-a(t-1)}, \quad k = 2,3,\ldots\ldots,m \tag{6}$$

Where $x_1^{(0)}$ is a prediction sequence, *a* is a coefficient, and *b* is a control parameter. The variables *a* and *b* can be determined by the ordinary least square method (OLS), as shown in equations (7) to (9) (Hsu & Wang, 2009; Huang, 2012; Liu & Yu, 2007; Xu *et al.*, 2013).

$$[a\ b]c^T = (B^T B)^{-1} B^T Y_n\ , \tag{7}$$

where

$$B = \begin{pmatrix} -\left[\frac{1}{2}x_1(1) + x_1\right] & 1 \\ -\left[\frac{1}{2}x_1 + x_1(3)\right] & 1 \\ \vdots & \vdots \\ -\left[\frac{1}{2}x_1(m-1) + x_1(m)\right] & 1 \end{pmatrix} \tag{8}$$

and

$$Y_N = \begin{pmatrix} x_1^{(0)}(2) \\ x_1^{(0)}(3) \\ \vdots \\ x_1^{(0)}(m) \end{pmatrix} \tag{9}$$

The mean absolute percentage error (MAPE) was also used in this study to verify the grey prediction results. The equation for MAPE is shown in equation (10) (Hsu & Wang, 2009; Pai *et al.*, 2007; Xu *et al.*, 2013).

$$MAPE = \frac{1}{n}\sum\left|\frac{x_i^{(0)} - \hat{x}_i^{(0)}}{x_i^{(0)}}\right| \times 100 \tag{10}$$

The MSW generation data for 2012-2017 were used in the model training, while data for 2018-2019 were used in model validation.

It is important to note that the "MSW generation data" mentioned and used in forecasting and scenario analysis of this study was the amount of MSW collected by the municipal service. It was not the total MSW generation in Mandalay municipality. When this study was conducted, there were no official records for the amount of MSW uncollected. However, it was estimated that the collected waste accounted for 85%, and the uncollected waste accounted for 15% in 2019. The uncollected waste was locally treated by reuse and recycle, animal feeding, illegal dumping and open burning. Nevertheless, the percentages of each treatment were unknown. Hence, the calculations were not carried out with the data of uncollected MSW in order to minimize the uncertainty.

Scenarios and assumptions

This study investigated the amount of GHG emissions under three different MSW management scenarios: business-as-usual scenario (BAU), alternative MSW management scenario 1 (S1), and alternative MSW management scenario 2 (S2). The assumption framework and MSW management targets (wt%) for BAU, S1 and S2 are summarised in Figure 2. The consideration time frame was from 2019 to 2030, which 2019 was the base year.

The BAU scenario represents the situation where MSW management practices in Mandalay as of 2019 remain unchanged until 2030. In 2019, it was estimated that the collected waste portion accounted for 85%, while the uncollected waste portion accounted for 15%. The collected MSW was treated by 80% landfilling and 5% recycling. The uncollected waste was treated in households through reusing, animal feeding, and illegal activities such as open dumping and open burning. This information was derived from a consultative discussion with the MCDC's head of the department.

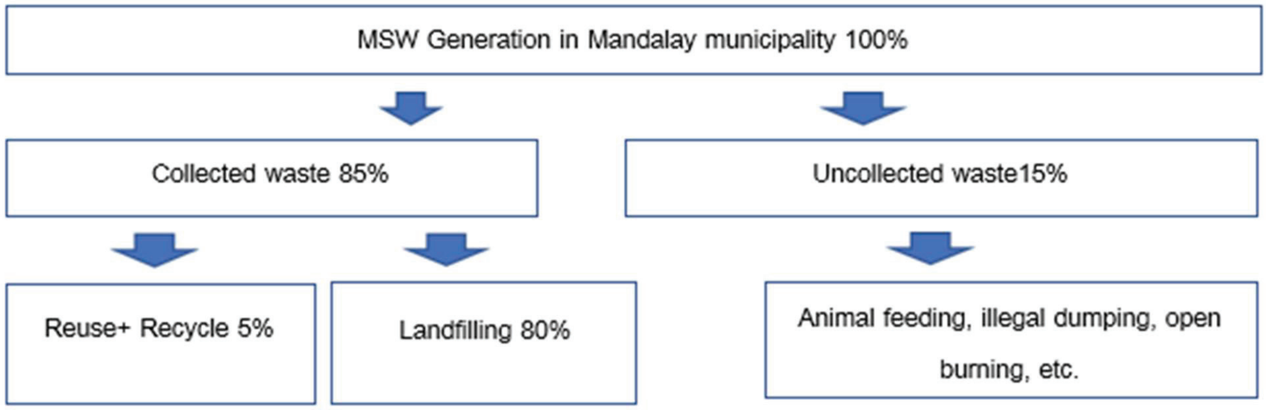
S1 and S2 were set up by referring to the Mandalay waste management strategy (MCDC, 2017). S1 represents the MSW management activities set in the midterm goals (2021-2025), while S2 represents midterm and long-term goals (2026-2030). The strategy did not specify any numeric targets for these MSW management goals. For our study, we set the possible targets for each MSW management activity in S1 and S2 by consulting with MCDC officers and reviewing previous studies related to Myanmar's waste management.

The strategy's midterm goals include enhancing waste collection, increasing waste recycling, operating composting and anaerobic digestion facilities, and substituting uncontrolled landfills with sanitary landfills. Tun & Juchelkova (2019a), who investigated Myanmar's nationwide waste management scenarios, suggested possible targets for recycling, composting, and anaerobic digestion as 5%, 5% and 1%, respectively. For S1 assumptions, we adopted the same targets for composting (5%) and anaerobic digestion (1%) from Tun & Juchelkova (2019a) but increased the recycling rate from the BAU level to 7%. The area with waste collection service was assumed to rise from the BAU level to 87%. The MSW sent to landfills was 74%. These targets were to be reached by 2025 after a constant increase from the 2019 levels of the BAU scenario. After 2025, the percentages for each MSW management activity were assumed to be stable until 2030.

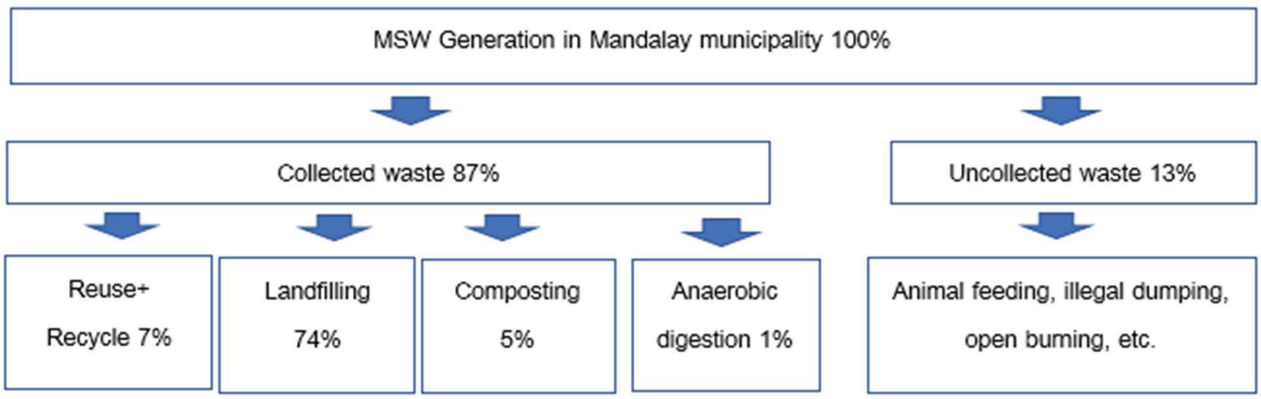
The strategy's long-term goals include enhancing the waste collection, increasing waste recycling and material recovery, ban of landfilling food waste and market waste, starting the operation of the WtEI plant, and substituting sanitary landfills with semi-aerobic landfills. After considering the area-based limitations of waste collection in Mandalay, S2's targets for collected MSW were assumed to be the same as S1 (87%). However, the assumptions for MSW management activities were set to be more challenging. The MSW management and disposal activities of the collected MSW were assumed to be 10% reusing and recycling, 10% composting, 1% anaerobic digestion, 3% incineration, and 63% semi-aerobic landfills. These targets were to be reached by 2030 after a constant increase from the 2019 levels of the BAU scenario.

For all scenarios, Mandalay's MSW composition was assumed to remain unchanged during 2019-2030. The basis for this assumption is that the waste compositions in most developing countries change slowly (Tun & Juchelkova, 2019a).

BAU Scenario: The MSW management targets from 2019 to 2030



Scenario 1: The MSW management targets by the end of 2025. The targets were kept constant until 2030.



Scenario 2: The MSW management targets by the end of 2030

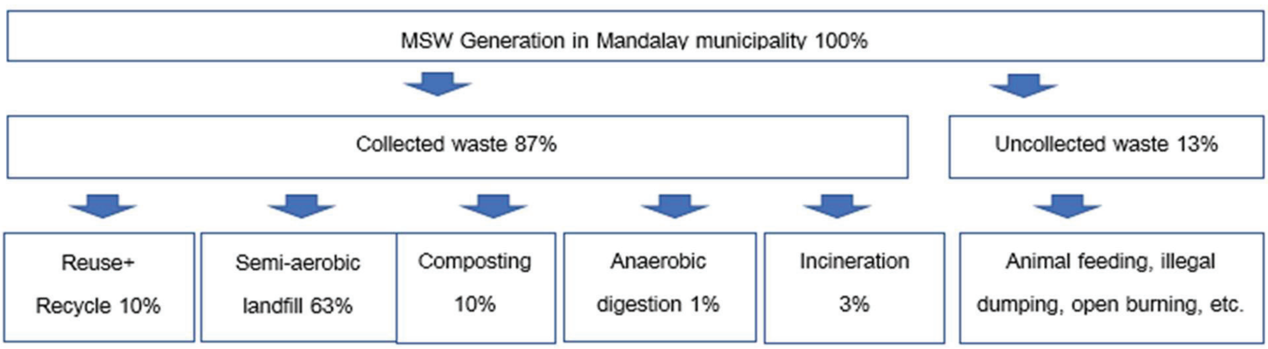


Figure 2 Assumption framework and MSW management targets (wt%) for business-as-usual scenario (BAU), alternative MSW management scenario 1 (S1), and alternative MSW management scenario 2 (S2)

We assumed that Mandalay's economy, lifestyle and tradition would not change significantly by 2030. Hence, the MSW composition in 2019 could correspond to the composition in 2030. Moreover, the necessary statistics and supporting information for predicting future changes in Mandalay or Myanmar waste composition are rare. To assume deviations in any particular waste component would have affected the percentages of all other parts. It would require systematic assumptions and sensitivity analysis. As for the scope of this study, we, therefore, limited our work to the constant waste composition to reduce the introduction of new uncertainties.

GHG emission estimations

This study focused on the GHG emissions from the treatment and disposal of waste as per the 2006 IPCC GL's Waste sector. The estimation of GHG emission from MSW treatment and disposal was based on the 2006 IPCC GL volume 5 (for emissions from biological treatment, incineration process and disposal on land). The GHG emissions from energy consumption during MSW collection and transportation were not included. Furthermore, emissions from uncollected waste were not estimated because no detailed information was available for this MSW portion.

The GHG emissions from waste disposals on land were calculated using the tier 1 method with a default value of six months for the time delay between waste deposition and methane (CH_4) release. The CH_4 emissions from disposal sites (Gg) were estimated using equations (11) and (12) (Eggleston *et al.*, 2006).

$$CH_4\ Emissions = \left[\Sigma CH_4 generated_{x,T} - R_T\right] \times (1 - OX_T) \quad (11)$$

Where CH_4 $generated_{x,T}$ is the amount of CH_4 generated from waste or material (x) in inventory year T (Gg), R is recovered methane (Gg), and OX is the oxidation factor (fraction).

$$CH_4\ generated_T = DDOC_m decomp_T \times F \times 16/12 \quad (12)$$

Where $DDOC_m decomp_T$ is the decomposable organic carbon decomposed in year T (Gg), F is a fraction of CH_4 by volume (volume fraction), and 16/12 is the molecular weight ratio CH_4/C (ratio).

Biological treatment of waste can contribute to the production of CH_4 and nitrous oxide (N_2O). The CH_4 and N_2O emissions (Gg) were estimated using the tier 1 method as in equations (13) and (14), respectively (Eggleston *et al.*, 2006).

$$CH_4\ Emissions = \textstyle\sum_i (M_i \times EF_i) \times 10^{-3} - R \quad (13)$$

$$N_2O\ Emissions = \textstyle\sum_i (M_i \times EF_i) \times 10^{-3} \quad (14)$$

Where M_i is the mass of organic waste treated (Gg), EF_i is the emission factor for treatment (g GHG/kg waste treated), and i is composting or anaerobic digestion. R is the total CH_4 recovered in the inventory year (Gg). For composting, the default CH_4 and N_2O EF values are 10 g CH_4/kg waste treated and 0.6 g N_2O/kg waste treated, respectively.

For anaerobic digestion, the default CH4 EF is 2 g CH_4/kg waste treated, while the emission from N_2O is assumed negligible. It was assumed that all biogas produced from anaerobic digestion was recovered and used in electricity production or household cooking. Therefore, the amount of GHG emissions from anaerobic digestion was reported as CO_2 emission due to biogas combustion. The CO_2 emissions were estimated by multiplying CH_4 emission by 44/16 (CO_2 / CH_4) (Marzouk, 2021).

The GHG emissions from WtEI were estimated by following the tier 1 method as in equations (15), (16) and (17), respectively (Eggleston *et al.*, 2006).

$$CO_2\ Emissions = \text{MSW} \times \textstyle\sum (WF_i \times dm_i \times CF_i \times FCF_i \times OF_i) \times {}^{44}/_{12} \quad (15)$$

Where MSW is the total amount of solid waste in wet weight (Gg/yr), WF_i is the fraction of waste type, dm_i is the dry matter content of each waste type i, CF_i is the total carbon content in dry matter, FCF_i is the fraction of fossil carbon in the total carbon, OF_i oxidation factor and 44/12 is the conversion factor from carbon to CO_2. It was assumed that the WtEI is semi-continuous incineration type (stocker).

$$CH_4\ Emissions = \textstyle\sum (IW_i \times EF_i) \times 10^{-6} \quad (16)$$

$$N_2O\ Emissions = \textstyle\sum (IW_i \times EF_i) \times 10^{-6} \quad (17)$$

Where IW_i is the amount of solid waste (Gg/yr), and EF_i is the emission factor of CH_4 and N_2O. Default CH_4 and N_2O EF values are 6 g CH_4/t waste treated and 50 g N_2O/t waste treated, respectively.

Results and Discussion

MSW composition

MSW compositions of Mandalay municipality, analyzed in March 2019 for the northern and southern transfer stations, are shown in Figures 3 and 4,

Table 2 Average MSW compositions (wt%) for Mandalay municipality in March 2019

MSW composition	Average MSW composition of the northern transfer station (wt%) (n = 3)	Average MSW composition of the southern transfer station (wt%) (n = 3)	Average MSW composition of Mandalay City (wt%) (n=6)
Food waste	13.7 ± 9.2	15.2 ± 6.3	14.4 ± 7.1
Garden and Park waste	43.7 ± 3.7	47.6 ± 1.7	45.4 ± 3.3
Paper and cardboard	3.1 ± 2.0	4.5 ± 1.2	3.7 ± 1.7
Wood	2.6 ± 3.7	4.1 ± 1.4	3.2 ± 2.6
Textile	15.8 ± 13.3	4.8 ± 3.7	11.0 ± 10.2
Nappies	1.9 ± 1.1	1.1 ± 1.5	1.5 ± 1.3
Rubber and leather	0.9 ± 0.7	1.5 ± 0.6	1.1 ± 0.7
Plastics	14.0 ± 4.5	17.2 ± 2.0	15.4 ± 3.6
Metal	0.8 ± 1.2	0.4 ± 0.3	0.6 ± 0.8
Glass	1.5 ± 1.6	1.9 ± 0.7	1.7 ± 1.1
Other	2.1 ± 0.8	1.8 ± 2.0	1.9 ± 1.4

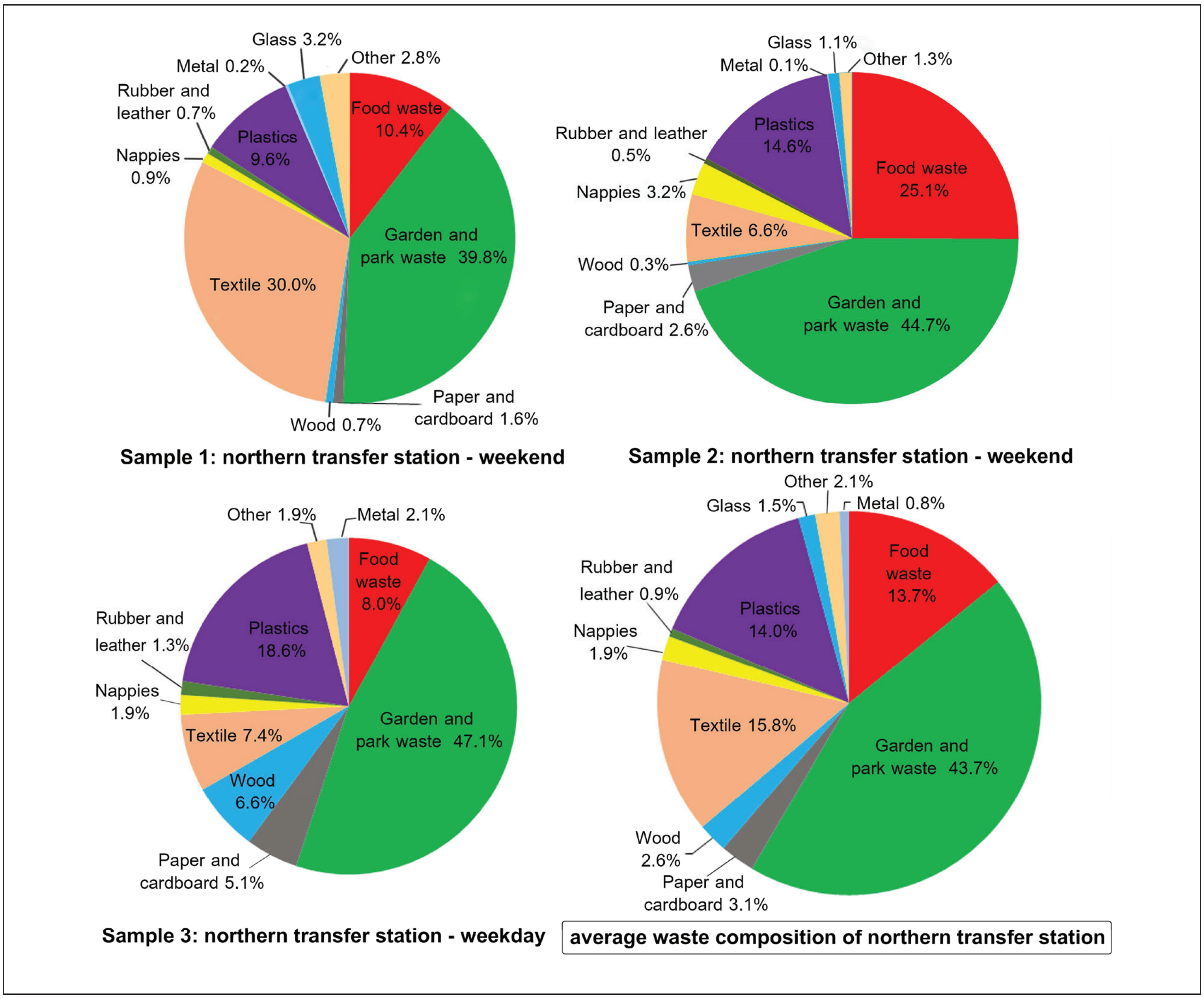


Figure 3 MSW composition (wt%) for the northern transfer station of Mandalay municipality (analyzed in March 2019)

respectively. The average MSW compositions of all samples are summarised in Table 2. The MSW compositions, percentage by wet weight, found at the transfer stations include primarily garden and park waste, food waste, plastic materials and textiles. Wood, rubber and leather, paper, nappies, metal, glass, and other materials such as construction and electronic waste are found in smaller amounts. All communities had a significant percentage of garden and park waste, ranging from 39.8-47.1%. On average, the garden and park waste contributed up to 45.4%. This result is in the same range as other studies conducted in 2012 (ADB, 2016), 2014 (ADB, 2016) and 2016 (MCDC, 2017). Garden and park waste were also previously reported as Mandalay municipality's most significant waste components (ADB, 2016; MCDC, 2017). Asia Development Bank (ADB, 2016) also noted the high fraction of green waste in other developing countries such as the Philippines, Cambodia, East Timor and Vietnam. The reason could be similar socio-economic conditions and climate patterns.

Our samples of garden and park waste comprised a large portion of flowers, leaves and garlands used for cultural and religious purposes and, to a lesser amount, small branches. Leaves are also used in wrapping vegetables to maintain their freshness and in local food packaging. As this substantial portion of the garden and park waste (45.4 ± 3.3%) and food waste (14.4 ± 7.1%) are being disposed of in landfills, there is a significant potential for reducing GHG emissions from Mandalay landfills by sorting waste and composting activities.

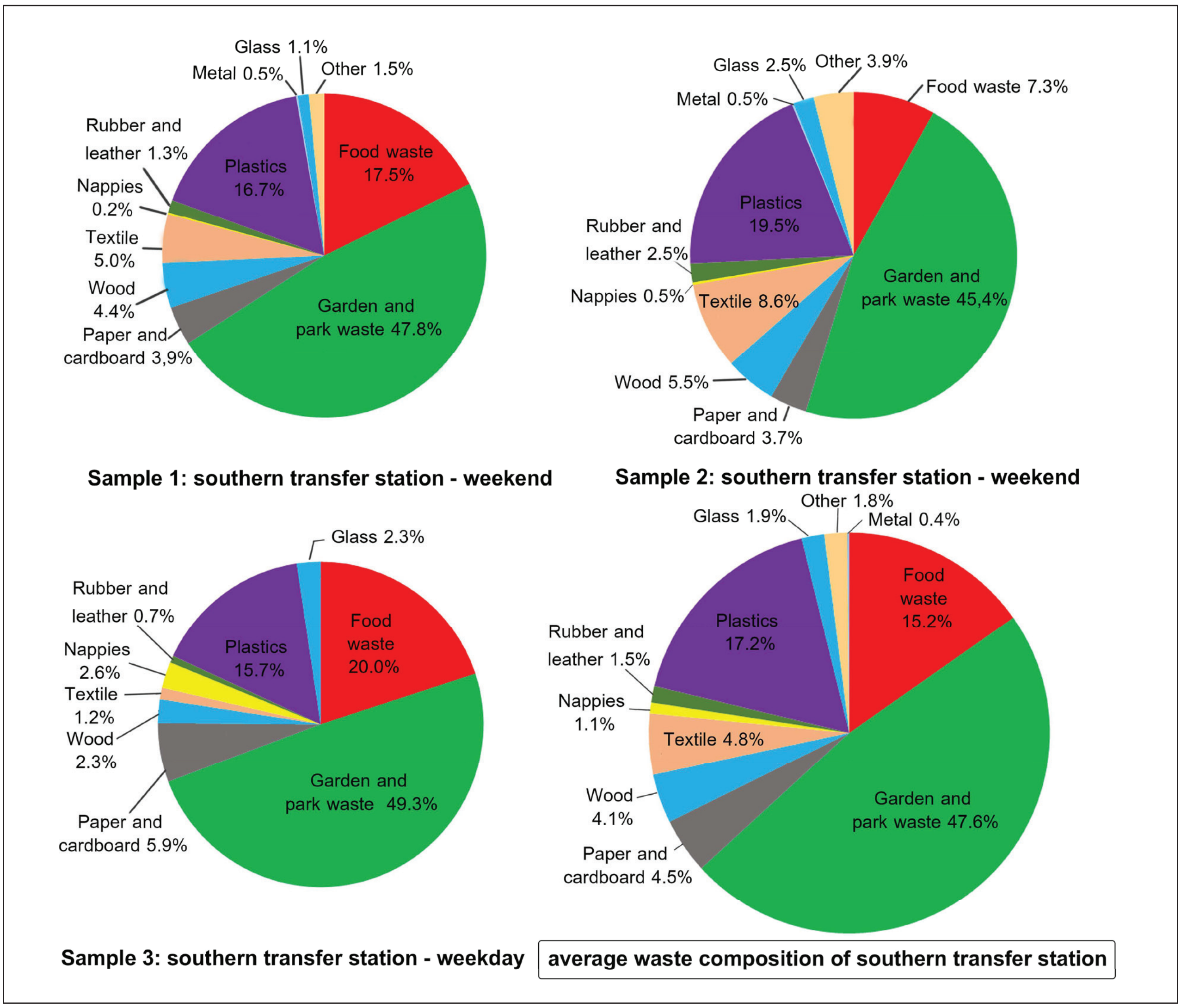


Figure 4 MSW composition (wt%) for the southern transfer station of Mandalay municipality (analyzed in March 2019)

Plastic waste was the second most significant portion of MSW (15.4 ± 3.6%), showing a high recyclable and energy recovery potential, such as for refuse-derived fuel (RDF). Paper and cardboard waste was detected in only 3.7% because it was collected mainly by scavengers before disposal. A significant proportion of paper waste found at the transfer stations was tissue paper, mainly from restaurants and houses. The rubber waste was mostly motorcycle tyres and a few car or truck tyres. Only a small amount of construction and electrical waste was found in the waste stream.

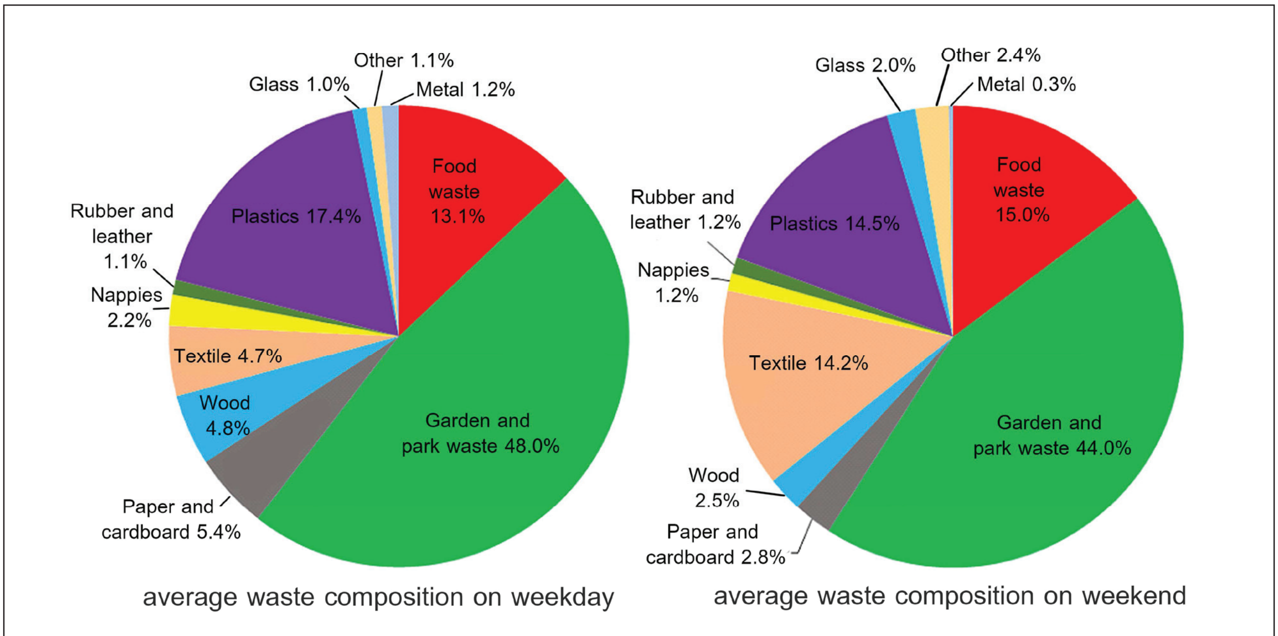


Figure 5 Average MSW composition (wt%) of Mandalay municipality on weekdays and weekends (analyzed in March 2019)

The informal sector, including scavengers, waste collectors, and waste dealers, is commonly involved in recycling papers and plastic waste. Waste collectors and scavengers collect recyclable materials such as newspapers, cardboard, containers made of tin, valuable metals, glass and plastic from homes, public warehouses, streets, commercial areas, and final disposal sites. Then, they sell the collected materials to waste dealers who clean, sort, store, and sell them in bulk to the local or international recycling industries.

It is noted that the textile waste fraction for the northern site is significantly higher than that of the southern site. The difference could be explained by the better socio-economic position of the northern towns, which allows them to throw away more textiles than their southern counterparts.

Figure 5 shows the differences between the MSW compositions detected on weekdays and weekends. There are differences in the percentages of food waste (1.9%), garden and park waste (4.0%), textile (9.5%), wood (2.3%), and paper and cardboard (2.6%). Food waste was found to be higher on weekends, possibly because most people buy food and cook more during the weekends. Textile waste was also increased by household activities during weekends, for example, house cleaning and closet clearing. The amount of garden and park waste was higher on weekdays than on weekends. The reason could be the clearing of branches along the roadside and the landscaping activities of the municipal staff, who usually work on weekdays. The effects of weekdays and weekends on MSW composition in Mandalay were not apparent on some types of waste such as glass, metal, rubber and leather, nappies, and other waste.

Table 3 Energy contents (MJ) in Mandalay's MSW in 2019 using the lowest and highest GCVs from literature and the IPCC default NCVs

Type of MSW	Energy content (MJ), based on GCV from the literature					
	Highest GCVs from literature (MJ/kg db)	**References**	**Possible highest energy content (MJ, db)**	**Lowest GCVs from literature (MJ/ kg db)**	**References**	**Possible lowest energy content (MJ, db)**
Food waste	20.93	Komilis *et al.* (2012)	447,616,763	18.40	Menikpura& Basnayake (2009)	393,509,243
Garden and park waste	17.2	Komilis *et al.* (2012)	1,161,161,601	15.80	Menikpura& Basnayake (2009)	1,066,648,447
Paper and card-board	16.21	Franjo Franjo *et al.* (1992)	222,740,530	15.00	Menikpura& Basnayake (2009)	206,114,000
Wood	14.2	Menikpura& Basnayake (2009)	162,245,483	14.20	Menikpura& Basnayake (2009)	162,245,483
Textile	23.34	Franjo Franjo *et al.* (1992)	845,142,500	17	Menikpura& Basnayake (2009)	615,438,959
Nappies	23.34	Franjo Franjo *et al.* (1992)	53,513,665	17	Menikpura& Basnayake (2009)	38,969,043
Rubber and leather	23.00	Menikpura& Basnayake (2009)	90,528,217	23.00	Menikpura& Basnayake (2009)	2,046,626,324
Plastic	39.35	Komilis *et al.* (2012)	2,546,150,675	31.63	Franjo Franjo *et al.* (1992)	1,099,988,856
Total			**5,529,099,434**			**4,620,079,715**
	Energy content (MJ), based on IPCC default NCVs					
Biomass fraction	10.00	IPCC (2006) Vol.2	1,792,459,327			
Non-biomass fraction	11. 60	IPCC (2006) Vol.2	565,456,046			
Total			**2,357,915,373**			

The moisture content from MSW samples collected from the northern and the southern transfer stations was 43.3 and 43.7%, respectively. The average moisture content for MSW of Mandalay municipality was estimated to be 43.2%.

Energy potential

The energy potential of Mandalay municipality's MSW in 2019, estimated using the lowest and highest GCVs from literature and the IPCC default NCVs, are shown in Table 3.

The energy potential based on GCV values found in the literature was 4,620 TJ when calculated with the lowest GCVs and 5,529 TJ when calculated with the highest GCVs. On the other hand, the energy potential based on IPCC default NCVs was 2,357 TJ. Plastic waste, garden and park waste, and textile waste were the primary energy sources in Mandalay's MSW. Plastic waste generally contains higher heating values than those other waste components. Therefore, waste with a high percentage of plastic is considered a promising energy source. Recently, problems with plastic waste have become more severe, particularly in developing countries. Treating plastic waste with WtEI can be a long-term solution to the increasing plastic pollution and can help solve the problems of an unstable electricity supply. However, the moisture content in the MSW must be less than 50% for the combustion process to be used for energy recovery; otherwise, a pre-drying process may be necessary (Aderoju *et al*., 2019).

The electricity production potential was estimated using the energy content value based on NCVs. The potential estimate was 5.2-10.3 MW for the WtEI, with an overall efficiency of 10-20%. The calculation based on GCVs was not carried out due to the lack of necessary information, such as the percentages of hydrogen, oxygen and nitrogen in each MSW component.

Critical challenges in setting up a WtEI in developing countries include its high capital, operation, and maintenance costs, high moisture content and the heterogeneous nature of MSW (Tun *et al*., 2020), and insufficient human resources with relevant skills. Myanmar has operated its first WtEI plant in Yangon (the largest city in Myanmar) since 2017. The plant's installed capacity is 700 KW, with a waste feeding rate of 60 t MSW/day. The plant uses almost 43% of its electricity for internal consumption, leaving approximately 57% for the grid (Huisman *et al*., 2017). Lessons learned from the Yangon WtEI plant will certainly benefit Mandalay city when it plans to implement WtEI technology.

Forecasts of MSW generation

The forecasting results of Mandalay municipality's MSW generation up to 2030, based on the GM (1,1) model and 2012-2017 MSW data, are shown in Figure 6. The model predicts that the MSW generation will increase from 419,165 t/year (1,148 t/day) in 2019 to 585,208 t/year (1,603 t/day) in 2025 and 797,066 t/year (2,183 t/day) in 2030. On average, the increasing rate is approximately 6.8% per year. The model accuracy evaluation using MAPE yielded a MAPE of 2.2%, indicating the excellent performance of the forecasting model (Intharathirat *et al*., 2015). The forecasted MSW generation for 2020 was 429,662 t/year and 1,177 t/day. This result was in line with Premakumara *et al.* (2016), who reported that the MSW generation of Mandalay municipality was 1,020 t/day in 2020. This municipality's rapid growth in MSW generation emphasizes the need for proper MSW management planning.

The MSW generation per capita per day (kg/capita/day) from 2020-2030 was estimated using the future population in the respective year. The future population was forecasted using the GM (1,1) and the historical data of Mandalay municipality's population from 2012-2019. The population in Mandalay was predicted to increase from 1,809,360 in 2019 to 1,897,965 and 1,975,108 in 2025 and 2030, respectively.

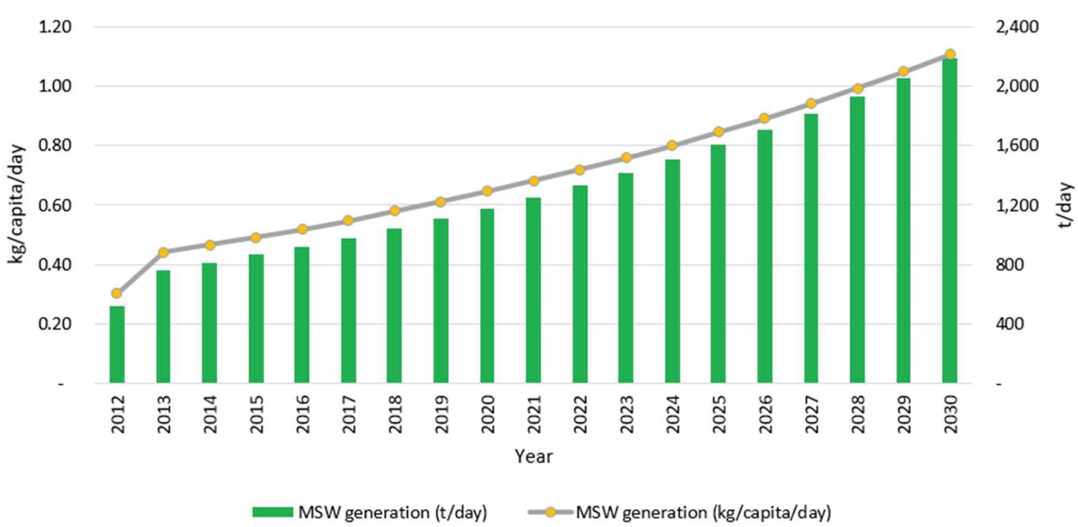


Figure 6 The MSW generation rate of Mandalay municipality: historical data (2012-2019) and forecasted data (2020-2030).

Consequently, the amounts of MSW generation per capita per day were estimated to increase from 0.63 kg/capita/day in 2019 to 0.84 and 1.11 kg/capita/day in 2025 and 2030, respectively. The forecast for 2025 agrees with Hoornweg & Bhada (2012), who reported the MSW generation rate of Myanmar as 0.85 kg/capita/day by 2025.

GHG emission Results

The GHG emission from MSW management and disposal of Mandalay municipality was estimated to be 94 Gg CO_2-eq/year in 2019. Under the BAU scenario, the emission was predicted to reach 517 Gg CO_2-eq/year (0.74 kg CO_2-eq/capita/day) in 2025 and 820 Gg CO_2-eq/year (1.13 kg CO_2-eq/capita/day) in 2030. Meanwhile, Tun & Juchelkova (2018) reported that the GHG emission from MSW management and disposal of Yangon municipality could reach 900 Gg CO_2-eq/year in 2025. As Yangon municipality's population was projected to reach 6,762,371 in 2025 by assuming a 2.4% annual growth rate, the GHG emission from MSW management would be equivalent to 0.36 kg CO_2-eq/capita/day. Therefore, regarding GHG emission per head, our estimate for Mandalay municipality was more than two times higher than that of Yangon municipality. Results from these two studies indicated that more attention should be given to the Mandalay municipality's MSW management and GHG mitigation planning.

The comparison of GHG emissions from MSW treatment and disposal of Mandalay municipality under BAU, S1 and S2 scenarios from 2019- 2030 are shown in Figure 7. Suppose the government could efficiently implement a sound waste management system as planned in the S1 (strategy's midterm goals). In that case, the GHG emissions could be decreased by 5% and 6% compared to BAU in 2025 and 2030, respectively. If the government continues to reach the strategy's long-term targets as in S2, The GHG reduction could increase to 54% and 55% in 2025 and 2030, respectively.

The GHG reduction in S1 was due to the increased rate of waste collection (+2%), reusing-recycling (+2%), composting (+5%), and anaerobic digestion (+1%) while reducing waste sent to landfills (-6%) compared to BAU. More GHG reduction potential could be achieved in S2 as a result of higher rates of reusing-recycling (+3%), composting (+5%), the addition of WtEI (+3%) compared to S1, and the conversion of all sanitary landfills to semi-aerobic landfills.

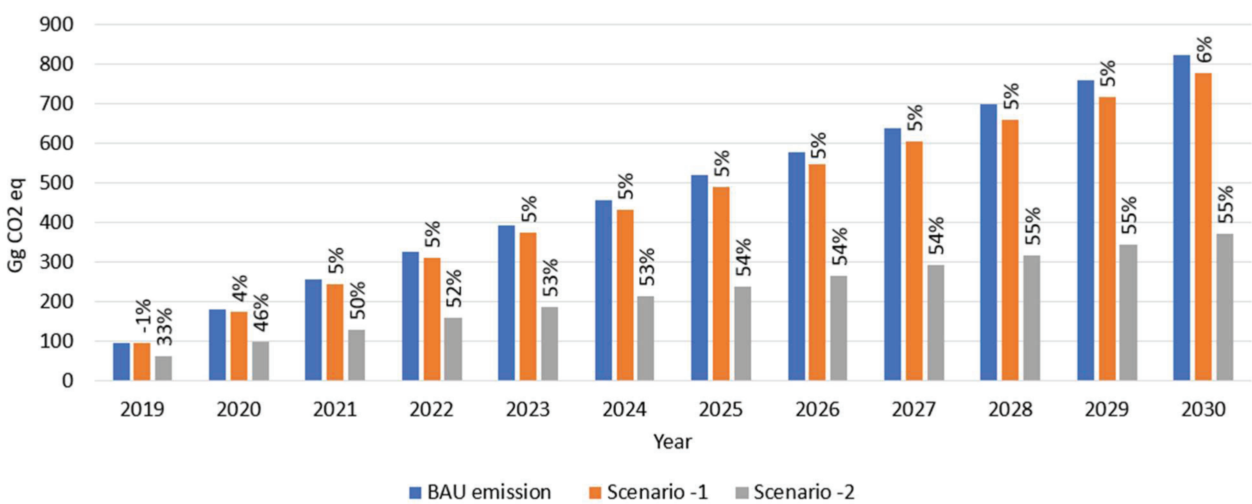


Figure 7 GHG emissions (Gg CO_2-eq) from MSW treatment and disposal of Mandalay municipality under three scenarios (BAU, S1 and S2) from 2019-2030.

Composting is an attractive waste treatment option for Mandalay municipality because organic waste makes up the majority of waste fractions. Composting facilities for organic waste have been successfully implemented in Indonesia (Zurbrügg *et al*., 2012) and Bangladesh (Menon, 2002). However, both countries have faced difficulties in popularizing compost products in existing markets. Both countries' governments overcome this challenge by planning to replace the chemical fertilizer with compost products within a target year. Lessons learned from those countries will undoubtedly benefit Mandalay city when it intends to implement composting facilities.

Using MSW as fuel or RDF provides great benefits as it can reduce fossil fuel consumption and GHG emissions from fuel combustion. However, the moisture of MSW should be minimized before energetic utilizations. The drier weight means less transportation cost and fuel requirement and a higher heating value suitable for thermal waste treatment technologies. Some simple methods for reducing the moisture content in MSW or RDF include biostabilization, biodrying, solar drying, thermal drying (Tun & Juchelkova, 2019b).

Recommendations for future work

This study conducted waste sampling and composition analysis in March 2019, during the dry season, when the average temperature range was 20 ºC-37 ºC. The results obtained from this sampling were used to estimate GHG emissions and energy potential in all years, as we assumed a constant waste composition. This assumption was designed to minimize the uncertainties from varying the unknown future waste composition. Furthermore, it was due to limitations on-site during the sampling period. Therefore, our results do not reflect the fluctuation of waste composition that may arise from seasonal change and growing urbanization rate. Population growth, gross domestic product (GDP), expenditure, urbanization rate, consumption habits and seasonal variations are factors controlling waste generation and its characteristics (Edo & Johansson, 2018; Tun *et al.*, 2020). The season could affect human consumption and waste generation and composition. For example, in Mexico, the amounts of food waste, paper, cardboard, plastics, and glass, were higher in summer than in winter (Aguilar-Virgen *et al.*, 2013). Changes in MSW amount and its composition significantly affect GHG emissions. Therefore, it is recommended that future work systematically plans for more waste sampling and composition analysis to improve the accuracy of waste forecasting and GHG emission estimates.

Moreover, it was suggested that a data recording system should be established for waste management. Such a system will be useful in evaluating the appropriate MSW treatment technologies for Mandalay and Myanmar.

This study used GM (1,1) to forecast MSW generation. The model used only the historical MSW generation data as its input variable. Future work could improve waste forecasting by using multivariate forecasting models that consider other vital parameters such as the socio-economic variable (e.g. GDP, household expenditure, employment) and demographic variable (e.g. population, urbanization, education).

Finally, it was noted that our current study was based on the municipality's statistics for collected MSW. There was no official record for the amount of uncollected waste and the total MSW generation in Mandalay municipality at the time of writing. We recommend that future studies investigate the MSW generation, waste collection efficiency and percentages of different waste treatment methods. A systematic on-site survey could improve these data. As a result, Mandalay city can effectively design its waste management action plans and strategy.

Conclusions

The MSW generation of Mandalay municipality was 1,148 t/day in 2019, and it was projected to reach 1,603 t/day in 2025 and 2,183 t/day in 2030. In 2019, garden and park waste was the most significant component contributing up to 45.4%, followed by plastic (15.4%), food waste (14.4%) and textile (11%). The rest comprised other waste components such as wood, rubber, leather, paper, nappies, metal, and glass. The moisture content of MSW samples was 43.2%. Because of its high organic waste fractions and high moisture content, composting is an interesting option for Mandalay municipality. The estimated energy potential from MSW was 2,357 TJ, equivalent to 5.2-10.3 MW of electricity. Under the BAU scenario, the GHG emission would increase from 94 Gg CO_2-eq in 2019 to 820 Gg CO_2-eq in 2030. GHG emissions could be reduced under both suggested scenarios. S1 (enhanced recycling and operations of composting and aerobic digestion facilities) could reduce GHG emissions by 6% in 2030. S2 (additional material and energy recovery, landfill conversion into semi-aerobic landfills) could reduce GHG emissions by 55% in 2030. S2 is the best scenario for the reduction of GHG emissions. However, implementing this scenario will require significant changes in Mandalay. Challenges include investments for efficient waste collection and treatment systems, private sector involvement, public participation, and the lack of in-country capacities and a skilful workforce. These issues should be addressed in the future city's plans to establish a sustainable MSW management system.

Acknowledgements

The authors would like to thank Prof. Dr. Chart Chiemchaisri, Asst. Prof. Dr. Komsilp Wangyao, Dr. Rotchana Intharathirat and Ms. Natvaree Chommontha for their guidance and support. The authors would like to express their gratitude to The Joint Graduate School of Energy and Environment, King Mongkut's University of Technology Thonburi and the Center of Excellence on Energy Technology and Environment (CEE), Ministry of Higher Education, Science, Research and Innovation (MHESI) for the financial support to perform this study. In addition, we would like to thank the Ministry of Natural Resources and Environmental Conservation (MONREC) and Mandalay City Development Committee (MCDC) for their support during on-site study.

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