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Municipal Food Waste Management and Its Greenhouse Gas Emission in Thailand: A Case Study of 8 Municipalities

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Food waste has a high potential for greenhouse gas (GHG) emission, particularly methane, which has been causing climate change issues worldwide. This quantitative research is aimed to investigate the situations of food waste and assess its greenhouse gas emission potential in Thailand. Food waste management in eight municipalities was analysed across four regions countrywide. The findings showed that the COVID-19 pandemic led to a dramatic reduction in municipal food waste (MFW). This led to a total of around 26,657 tonnes/day in 2021, which was nearly 39% of the total MSW and the average MFW generation per capita was 0.4 kg/capita/day. Household food waste (HFW) represented a major component of MFW. In large urban municipalities and cities (notably tourist cities), significant food waste per capita exceeded the peri-urban municipalities ($P < 0.05$). Moreover, the treatment of MFW could result in significantly higher GHG emissions than from fossil fuel emissions created by the collection and transportation of MFW. This comparison between the four food waste management technologies that emits the most greenhouse gases showed that landfill had the most GHG emission potential, followed by incineration, composting, and anaerobic digestion, respectively. The research findings clearly illustrated that the municipalities at all levels needed to take the following actions: 1) conduct a survey and study the situations of food waste problems in local area, 2) formulate the policy for food waste management and treatment using the appropriate selection of technologies available with a minimum of impact on the environment and the Earth's atmosphere, and 3) utilise the GHG emission potential for food waste disposal, such as energy recovery as well as possible trading-in for carbon credit.

Keywords: municipal food waste (MFW), municipal solid waste (MSW), household food waste (HFW), greenhouse gas (GHG) emissions, food waste treatment technology, urban food waste.

Introduction

At the top of the world's urgent agenda is climate change, which impacts human survival and sustainability on Earth. All sectors worldwide at the national, regional, and local levels agree that a push for net-zero carbon emissions is imperative to accomplish this goal at limiting Earth's rising temperatures, not exceeding 1.5°C or 2°C (UNFCCC, 2016). According to the research of Poore and Nemecek (2018), food production along the supply chain is destined for the consumption of the world's population of approximately 7 billion. Food production accounts for 26% of global GHG emissions, and 6% of global GHG emissions come from food losses and waste.

The tremendous amount of food waste, or approximately 931 million tonnes worldwide (UNEP, 2021), is due to people's consumption behavior (Geislar, 2019), increased population, and the expansion of urban communities (Mattar et al., 2018; Wang, 2019; Zhang et al., 2018). Moreover, food waste is the main composition of municipal solid waste (MSW) (Ali et al., 2017; Caicedo-Concha et al., 2019), to be found mostly in open dumps and sanitary landfills (Kaza et al., 2018), which are the main causes of methane at 28 times the global warming potential of carbon dioxide (CO_2). Methane emission is found most during the first one to three years of landfill (Garg et al., 2006).

During 2010–2019, prior to the outbreak of the COVID-19, the Pollution Control Department reported that the amount of solid waste in Thailand increased from 41,352 tonnes/day to 78,630 tonnes/day. Food waste was the main composition at approximately 64% of MSW. The food waste per capita was approximately 0.70 kg/capita/day (PCD, 2016a; 2020b) and was considered very high comparing to developing countries and within ASEAN countries, for example, there was 0.49, 0.5–0.8 and 0.40 kg/capita/day of food waste in Vietnam, Malaysia, and Cambodia, respectively (Bong et al., 2017a; Kawai and Huong, 2017; PPCA, 2018). Moreover, the ineffectiveness of food waste treatment in municipalities is a source of concern as most inhabitants dispose food waste with solid waste, and it is sent to waste disposal facilities. Over 90% of municipalities dispose waste through open dumps and landfills (PCD, 2020b). As a result, the GHG emissions from solid waste disposal tend to increase. In 2018, the Office of Natural Resources and Environmental Policy and Planning (ONEP) forecasted that by 2030 the GHG emission would equal 20 million tonnes of CO_2-eq, which would be an increase of 55.40% from 2005. Every year, the waste sector releases mostly CH_4, followed by N_2O and CO_2, respectively (ONEP, 2021a). This contributes to climate change and poses obstacles for Thailand's goal to reduce GHG to reach carbon neutrality by 2050, or the net-zero GHG emission by 2065 (ONEP, 2021b).

Because of the forecast and data, the researchers conducted a study and a survey of the food waste amount and compositions in eight municipalities covering all regions in Thailand: namely the north, the central plains, the northeast, and the south, which was the first study of food household waste survey throughout the country. The study also completed an evaluation of the GHG emission potential from different processes of food waste management including the process of MFW collection and transportation to solid waste disposal facilities, and the process of MFW treatment with different technologies. The GHG emission of different municipalities and waste treatments play valuable roles for food waste management in the future and reflect the efficiency of waste management as well. The study findings for planning and selection of appropriate food waste management could be utilised by executives at the municipal level and other agencies responsible for the formulation of a national policy leading to a low carbon urban society for sustainable development. Moreover, the appropriate food waste treatment supports the Paris Agreement targets to reduce the increase in global temperature to 1.5 degrees above pre-industrial levels.

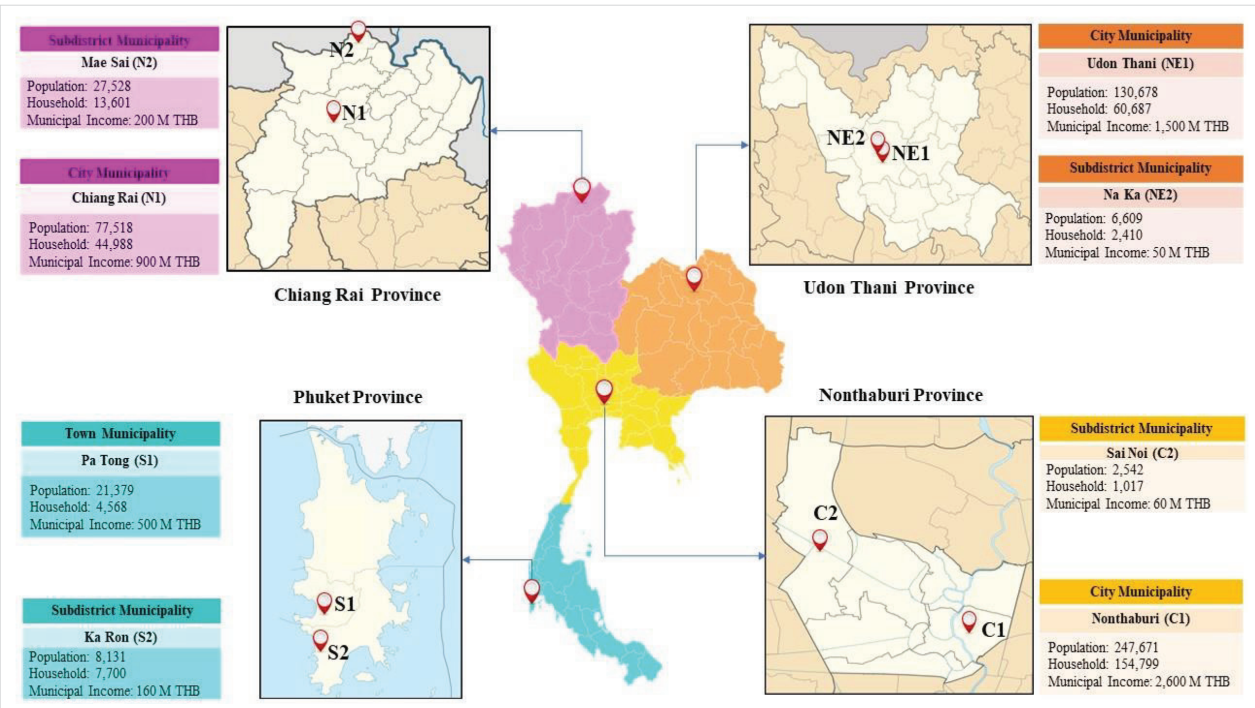
Methods

Description of the studied municipalities

This research applied the principle of probability sampling with the method of multi stage sampling to investigate the amount and compositions of HFW. To evaluate the GHG emission from food waste management, this research used a target sample of eight municipalities in four provinces (Nonthaburi, Udon Thani, Chiang Rai, and Phuket) covering four regions nationwide, namely Nonthaburi City Municipality (C1), Chiang Rai City Municipality (N1), Udon Thani City Municipality (NE1), and Patong Town Municipality (S1), as well as the peri–urban municipalities of Sai Noi Subdistrict Municipality (C2), Mae Sai Subdistrict Municipality (N2), Na Kha Subdistrict Municipality (NE2), and Karon Subdistrict Municipality (S2) as shown in *Fig. 1*.

C1 and C2 are in Nonthaburi, which is one of the central provinces of Thailand, and are part of the Bangkok Metropolitan Region with high economic growth. Their gross provincial product (GPP) is 345,411 million baht and their GPP per capita is 197,159 baht. Nonthaburi is ranked 75th out of 77 provinces in terms of size (including Bangkok), but is the 2nd most densely populated province (2070.76 persons/sq km) after Bangkok. It is also home to many people from other areas of the country, who have moved to the province for work and study. N1 and N2 are in Chiang Rai, which is one of the northern provinces. N2 borders Myanmar and Lao PDR and has a special economic zone (SEZ), which is an area where business and trade laws are different from the rest of the country. This SEZ is located within Thailand's national borders and aspires to increase trade balance, employment, investment, and maintain effective administration. N2 facilitates trade and investment that connect with ASEAN and six other countries of GMS (Greater Mekong Subregion), with a GPP per capita of 93,182 baht. As for the northeast, NE1 and NE2 are situated in Udon Thani, which has government agencies, academic institutions, and a logistics and transportation center. They also have communication routes that connect with Nong Khai via a friendship bridge between Thailand and Lao PDR, as well a trade and economic center, and the biggest market of agricultural products in the region. They have a GPP per capita of 90,269 baht. In downtown and city municipality areas, there are many shops, department stores, community malls, outlets, and retail-wholesale centers. Finally, there is S1 and S2 and these are in Phuket, which is the biggest island in southern Thailand. Being a major tourist location, it is ranked 2nd after Bangkok for generating income. In 2019, it earned 470,000 million baht with 14.5 million tourists, and had a gross domestic product (GDP) of 251,813-million-baht (428,351 baht/capita/year). Phuket's economy relies on the tourism industry for 80% of its income, and has over 2,000 hotels (NESDC, 2018).

Fig. 1. *Eight study sites across Thailand*



Data for calculation of municipal solid waste (MSW) and municipal food waste (MFW) generation in Thailand

This study assessed MSW and MFW generated in Thailand during 2004–2021 through the calculation of linear regression to obtain the trend of food waste against time (year). This computation used secondary data, the compositions of MSW from 18 government agencies, and the database on solid waste of local administrative organisations nationwide. This data were collected according to the calculation following the Food Loss and Waste Accounting and Reporting Standard (FLW Standard) (Hanson, 2016; UNEP, 2021).

Data for calculation of household food waste (HFW) generation in eight studied municipalities

The population used in this study consisted of 289,770 households in eight municipalities. Obtaining the sample of at least 400 households, the number of samples was calculated using the Taro Yamane formula, which determined a reliability level of 95%. Data collection was divided into two methods and was completed in November, 2021. Prior to collecting data, we carried out the Item Objective Conformity Analysis Tool (IOC). Then data collection was conducted with the use of a close-ended questionnaire with the improvement and rectification according to three experts' recommendations prior to data collection, verification of the reliability through the try-out with 30 copies, and testing of the reliability at the level of 95% using the Cronbach's Alpha and acquiring 0.85. It showed that the tool was reliable and could be used in the study. Secondly, the waste composition analysis was conducted using weighing, survey composition, and daily records for a total of five days, divided into three working days and two days of holiday. To compare the waste amount differences between the situations, statistical analysis was performed. The statistical analysis was performed using SPSS 21.0 software (SPSS Inc., Chicago, IL). Not only was the descriptive statistics used, but also the *t* test, one-way ANOVA (analysis of variance) with a 95% confidence level ($P < 0.05$) and the Pearson product-moment correlation coefficient.

This research was certified and approved by the Ethics Committee in Human Research, National Institute of Development Administration according to the certified document COA No. 2021/0034 to protect the rights of the research participants and the data collected from the questionnaire. The collection of HFW data resulted in a return of 667 copies which exceeded the planned sample size of 400 copies. The researchers then conducted a complete analysis of the questionnaire and survey results to cover additional data.

Evaluation of GHG in municipal food waste management

The evaluation of the GHG emission from the MFW management activities was divided into two processes: 1) the collection and transportation process of MSW to disposal sites whereby GHG is released from the vehicles' exhaust, and 2) the process of food waste treatment or disposal. The GHG data for this study was generated from the biochemical and combustion process according to the technology used for food and waste treatment. C1, C2, and N1 municipalities used a sanitary landfill process at the disposal site of each province. Alternatively, municipal solid waste of S1 and S2 municipalities was transported to the incinerators of Phuket central waste disposal facility. Meanwhile, NE1, NE2, and N2 municipalities disposed their food waste through composting at the solid waste disposal site in the Udon Thani City Municipality, and the integrated solid waste disposal site in the Mae Sai Subdistrict Municipality, respectively.

As for the evaluation of GHG emissions from MFW management, the calculations were in accordance with the Thailand Voluntary Emission Reduction Program (T-VER) developed by Thailand Greenhouse Gas Management Organization (TGO) (TGO, 2021d). The guidelines for T-VER are based on results derived from an analysis study of American Carbon Registry (ACR), Clean Development Mechanism (CDM), Gold Standard (GS) and Voluntary Carbon Standard (VCS). The T-VER methodology consists of an equation and the details are as follows.

Evaluation of GHG emission from waste collection and transportation

GHG evaluation from fossil fuel combustion in the collection and transportation process was as in the following *equation* (*1*):

$$\text{GHG Emissions} = \text{Activity Data x Emission Factor} \quad (1)$$

where GHG Emissions is GHG emissions from fossil fuel base vehicles ($kgCO_2$/year); Activity Data is total fossil fuel consumed per year (litres/year); Emission Factor is the CO_2 emission factor of the fossil fuel (Diesel: 2.7403 $kgCO_2$-eq /litre).

Evaluation of GHG emission from food waste treatment with different treatment technologies

Methane from sanitary landfill

Calculation for emissions from solid waste disposal sites was done according to the following *equation* (*2*):

$$BE_{CH4,SWDS,y} = W_y \times [p_{wood,y} \times 4.02 + p_{paper,y} \times \times 3.72 + p_{foodwaste,y} \times 1.00 + p_{textile,y} \times 2.23 + + p_{gardenwaste,y} \times 1.68] \times CF \times 0.1 \quad (2)$$

Where: $BE_{CH4,SWDS,y}$ is the CH_4 emission from the MSW landfill in the year *y* (tCO_2-eq/year); W_y is the wet weight of MSW in the year *y*; $p_{foodwaste,y}$ is the food waste generated (%/total MSW) in the year *y*; CF is the proportion of carbon to wet weight of solid waste. This value varies according to management practices. IPCC recommends a default CF value for managed (has landfill cover with liner), unmanaged-deep (> 5 m waste), unmanaged-shallow (< 5 m waste), while uncategorized are 7.14, 5.17, 3.57 and 2.86, respectively. For this model, a default value of 7.14 (average value given by IPCC (IPCC, 2006)) was used.

Note: This research focused on GHG emission from food waste treatment. In this model, the ratio of other organic waste material is not used.

GHG emission from compost

GHG emission (CH_4 and N_2O) during food waste composting was calculated as follows:

$$PE_{COMP,y} = W_y \times (EF_{CH4} \times GWP_{CH4} + + EF_{N2O} \times GWP_{N2O}) \quad (3)$$

Where: $PE_{COMP,y}$ is GHG emissions from food waste compost (tCO_2-eq/year); EF_{CH4} is the CH_4 emissions during food waste composting (tCH_4/tonne of food waste). The default value of 0.002 t CH_4/t waste, which was given for Thailand Voluntary Emission Reduction Program (T-VER-METH-WM-03, 2021) for production of compost or soil amendments from organic waste, was used in this study. GWP_{CH4} is the global warming potential of CH_4 (28 $kgCO_2$-eq); EF_{N2O} is the N_2O emissions during food waste composting (tN_2O/tonne of food waste), the default value of 0.0002 (average value given by IPCC (IPCC, 2006)) was used. GWP_{N2O} is the global warming potential of N_2O (265 $kgCO_2$-eq). Global warming potential of CH_4 and N_2O with reference to the IPCC Fifth Assessment (AR5) 2014.

GHG emission from MSW incineration

Incineration of waste is calculated from the amount of MSW as bulk waste without classifying it into the individual waste composition. *Equation* (*4*) to *equation* (*6*) will be calculated as follows:

$$CO_2 \text{ Emissions} = \sum(SWi \times dmi \times CFi \times \times FCFi \times OFi) \times 44/12 \quad (4)$$

Where: CO_2 Emissions is combustion emissions (tCO_2/year); SWi is wet weight of food waste (tonne); dmi is dry matter content in the food waste (partially wet weight) incinerated; the default food waste fraction value of 0.4 (average value given by IPCC (IPCC, 2006)) was used. CFi is the fraction of carbon in the dry matter (total carbon content); the default food waste fraction value of 0.38 (average value given by IPCC (IPCC, 2006)) was used. FCFi is the fraction of fossil fuel carbon in the total carbon; the default food waste fraction value of 0 (IPCC, 2006) was used. OFi is the oxidation factor; the default solid waste fraction value of 1 (average value given by IPCC (IPCC, 2006)) was used. The value 44/12 is a conversion factor from C to CO_2.

$$CH_4 \text{ Emissions} = \sum(IWi \times EFi) \times 10^{-6} \quad (5)$$

$$N_2O \text{ Emissions} = \sum(IWi \times EFi) \times 10^{-6} \quad (6)$$

where CH_4 Emissions and N_2O Emissions are emissions of CH_4 and N_2O in an inventory year (tCO_2-eq/year), respectively; IWi is the MFW generation rate incinerated (% /total MSW); EFi is the aggregate CH_4 or N_2O emission factor. For CH_4 emission, this value varies according to incineration type. IPCC has recommended default EFi values for operated (continuous incineration (stoker), continuous incineration (fluidised bed), semi-continuous incineration (stoker), semi-continuous incineration (fluidised bed), batch type incineration (stoker), and batch type incineration (fluidised bed) to be 0.0002, 0, 0.006, 0.188, 0.06 and 0.237, respectively. In this model, the default value of 0.006 (average value given by IPCC (IPCC, 2006)) was used. For N_2O emission, this value varies according to management practices. IPCC has recommended default EFi values for managed continuous and semi-continuous incineration, batch-type incineration, and open burning to be 0.05, 0, 0.06 and 0.150, respectively; the default value of 0.05 (average value given by IPCC (IPCC, 2006)) was used.

Methane from anaerobic digestion for utilisation

The emission of methane from an anaerobic digester includes emissions during maintenance of the digester, physical leaks through the roof and side walls, which release through safety valves due to excess pressure in the digester. These emissions are calculated using a default emission factor (EF_{CH4}, default), as in the following *equation* (*7*):

$$PE_{CH4,y} = W_y \times EF_{CH4} \times GWP_{CH4} \tag{7}$$

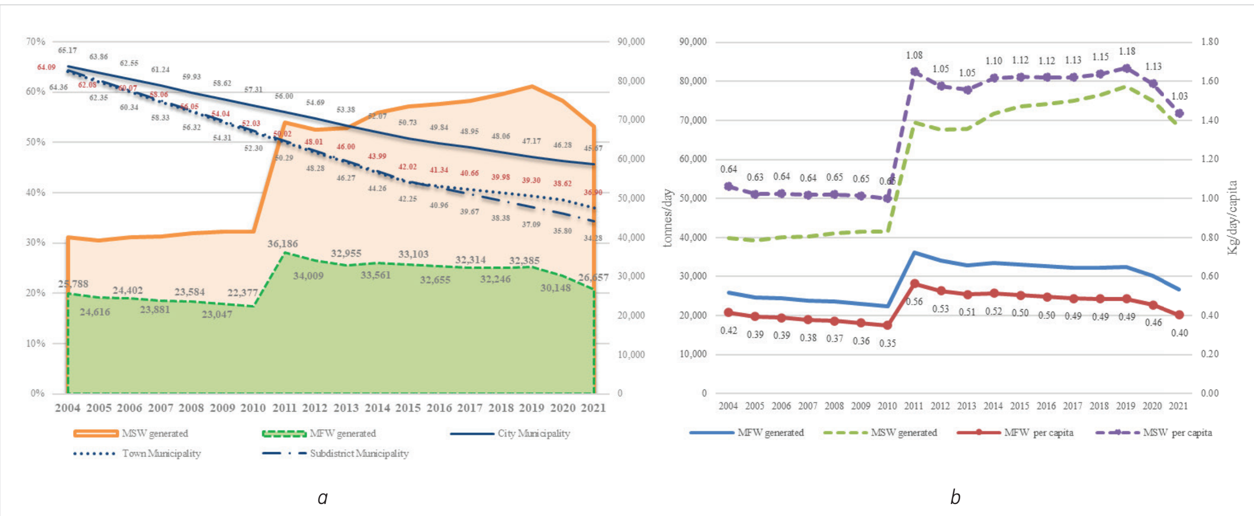
Where: PE_{CH4} is the CH_4 emission from the anaerobic digester in the year y (tCO_2-eq /year); W_y is the wet weight of food waste in the year y (tonnes/year); EF_{CH4} is a default emission factor for the fraction of CH_4 produced by leaking from the anaerobic digester. In this model, the default value of 0.001 t CH4/t waste, which was given for Thailand Voluntary Emission Reduction Program (T-VER-METH-WM-06, 2021), was used. GWP_{CH4} is the global warming potential of CH_4 (28 kg CO_2-eq).

Results and Discussion

Municipal food waste (MFW) generation in Thailand

Based on calculations of MFW for 2472 municipalities nationwide (30 city municipalities, 195 town municipalities, and 2248 subdistrict municipalities), it was found that in 2021 the generated MFW was approximately 26,657 tonnes/day (an average 38.95% of total MSW) as shown in *Fig. 2(a)*. The rate of MFW produced per capita was 0.40 kg/capita/day, or 146 kg/capita/year as shown in *Fig. 2(b)*. *Fig. 2* shows that the main component of MSW was food waste, which contributed to 45.67% of the total MSW in city municipalities, 36.90% in town municipalities, and 34.28% in subdistrict municipalities. In city municipalities, the MFW generation rate exceeded the town and subdistrict municipalities significantly ($P < 0.05$). HFW is also the main component

Fig. 2. *(a) Situation of municipal food waste generation in Thailand 2004–2021, and (b) the MSW and MFW generation rate (kg/capita/day) in Thailand (2004–2021)*



of MSW accounting for more than 50% of total MSW (wet weight) in developing countries (Bong et al., 2017b; Maalouf and El-Fadel, 2017; Wen et al., 2016; Yang et al., 2018), for instance, 40–60% in Malaysia, approximate 51% in China. Unlike for a developed economy region, a lower food waste fraction of 30% was found (Maalouf and El-Fadel, 2017). During 2004–2018, prior to the COVID-19 outbreak, the municipalities experienced an average MFW growth rate of 0.66% per year. Moreover, the municipal and food waste increased considerably from 2010 to 2011, as seen in *Fig. 2*, because waste amount at disposal facilities has been used instead of fixed waste amount per capita since 2011.

Conversely, during the outbreak of COVID-19, it was found that the MFW decreased at an average of −6.65% due to a continuously decreasing GDP, a decrease in tourists, an increase in unemployment, and an increase in the return of migrant workers to their respective countries (Liu et al., 2021). This was in line with the situations and changes in MSW for the country as shown in the graphs in *Fig. 2(a)* and *2(b)*. The Pearson correlation showed a robust association between the generation of MSW and MFW in Thailand, with r = 0.918 ($P < 0.05$).

Municipal food waste (MFW) generation in eight studied municipalities

Based on collected data, it was revealed that from 2020–2021 that most municipalities experienced a decrease in the amount of MFW and MSW as shown in *Table 1*. The data show that the main component of MSW is MFW which is consistent with the national waste statistics data (*Fig. 2*). The average MFW of urban municipalities (C1, N1, NE1, S1) was significantly higher ($P < 0.05$) than the average MFW of the peri-urban municipalities (C2, N2, NE2, S2) accounting for 280.84 tonnes/day (0.62 kg/capita/day) and 15.25 tonnes/day (0.42 kg/capita/day), receptively, in 2021. It is also higher than the nationwide average of 0.40 kg/capita/day. The results confirmed that the MFW in urban areas was mostly higher than in rural areas in Thailand (Huho et al., 2020; Mattar et al., 2018; Van der Werf et al., 2018; Wang, 2019). Therefore, it is essential, and of the utmost priority, to decrease MFW and to conduct proper food waste treatment in the urban municipalities as well as tourist destination cities. In 2021, C1 had the highest MFW at 147.27 tonnes/day, whereas NE2 had the least at 1.13 tonnes/day as shown in *Table 1*. In 2020, the largest decrease in MFW was found in S1 and S2 municipalities at 70.38% and 68.28%, respectively. This was due to a substantial decrease in tourists which accounted for a reduction of −71.36% and −93.61% for Phuket and the whole of Thailand for the years 2020–2021 (MOTS, 2022). Moreover, certain COVID-19 restrictions and diminished economic activity due to the pandemic have led to an extraordinary decrease in waste from the business sectors in the total

Table 1. *Total of MSW and MFW in eight studied municipalities in 2020–2021*

Municipality	MSW (tonnes/day)		Growth rate (%)	MFW (tonnes/day)		Growth rate (%)	Population	MFW per capita (kg/capita/day)		
	2020	2021		2020	2021			2020	2021	Avg.
(1) Urban municipalities										
C1	325.67	322.46	−0.99	150.72	147.27	−2.29	247,671	0.61	0.59	0.60
N1	97.63	103.19	5.69	45.18	47.13	4.32	77,518	0.58	0.61	0.60
NE1	157.39	155.35	−1.30	72.84	70.95	−2.59	130,678	0.56	0.54	0.55
S1	135.43	41.99	−69.00	52.3	15.49	−70.38	21,379	2.45	0.72	1.59
Total (1)	716.12	622.99	−13.00	321.04	280.84*	−12.52	477,246	1.05	0.62	0.83
(2) Peri-urban municipalities										
C2	5.01	4.86	−2.99	1.79	1.67	−6.70	2542	0.70	0.66	0.68
N2	28.46	23.12	−18.76	10.19	7.93	−22.18	27,528	0.37	0.29	0.33
NE2	3.04	3.29	8.22	1.41	1.13	−19.86	6609	0.21	0.17	0.19
S2	39.8	13.19	−66.86	14.25	4.52	−68.28	8131	1.75	0.56	1.16
Total (2)	76.31	44.46	−41.74	27.64	15.25*	−44.83	44,810	0.76	0.42	0.59

**With the statistical significance at the level of 0.05* amount of municipal waste generated (Liu et al., 2021). This study also found a slight increase in the amount of MSW for N1, MFW for N1, and MSW for NE2, accounting for 5.69%, 8.22%, and 4.32%, respectively, of the waste generated in 2020. Evidence supports that this might be related to the migration of domestic workers from the different areas to their hometowns (Triukose et al., 2021).

Household and non-household food waste generation and composition in studied municipalities

Unlike the calculation of MFW generation at the national level, data collection for food waste in eight municipalities was based on the questionnaire survey of 435 households as well as five days spent on weighing the daily records of 232 households. It was revealed that the data of household food waste (HFW) from the two methods had no significant difference ($P < 0.05$), which was 0.79 and 0.73 kg/household/day for method 1 and method 2, respectively. The results also showed that the HFW generated by the urban and peri-urban municipalities was significantly different ($P < 0.05$) accounting for 0.30 and 0.21 kg/capita/day, respectively (see *Table 2*). C1 generated the highest HFW at 1.11 kg/household/day (0.38 kg/capita/day), while NE2 and S2 generated the least HFW with the average of 0.55 kg/household/day (0.17 and 0.18 kg/capita/day, respectively). The total number of household members and income might be a factor in this discrepancy in HFW. Although it is often stated that food waste is more severe in the urban households than the rural households, some studies even revealed a higher wastage in rural areas than in urban areas in China (Li et al., 2021; Qi et al., 2020; Song et al., 2018) because people from rural areas ate more than 50% of their meals at home. Moreover, the HFW represented a major component of MFW, which averaged at 55.71% of the total MFW. This was in accordance to the Food Waste Index Report in which the UNEP specified that a worldwide HFW was 61%; followed by food services and retail at 26% and 13%, respectively (UNEP, 2021). HFW is related to a lack of planning, excessive purchasing, over-preparation, inappropriate food conservation, and not being willing to consume leftovers (Principato, 2018). However, there were four municipalities (S1, NE2, C2, and S2) where non-household food waste was individually and notably higher than HFW. In three municipalities (NE1, NE2, and N2) using anaerobic organic composting, HFW was dominant, in contrary to the ones using incineration (S1 and S2) where non-household food waste was higher than HFW. The reason is that NE1 is the biggest market of agricultural products in the region, and in the downtown, there are many restaurant, community malls, and retail-wholesale centres. S1 and S2 are major tourist areas, so there are many hotels and restaurants. C2 is an agriculture and agricultural industry area, so there are many commuters and non-registered people within the population.

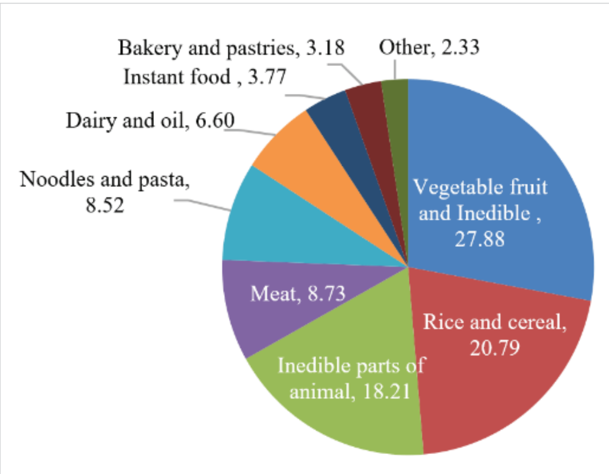
Table 2. *The HFW generation in eight studied municipalities*

Municipality	MFW (tonnes/day)	MFW sectors (% of total MFW)		HFW generated	
		Household	Non-household	(kg/household/day)	(kg/capita/day)
(1) Urban Municipalities					
C1	147.27	63.93	36.07	1.11	0.38
N1	47.13	58.57	41.43	0.99	0.36
NE1	70.95	47.30	52.70	0.85	0.26
S1	15.49	28.92	71.08	0.66	0.21
Average		49.68	50.32	0.90*	0.30*
(2) Peri-urban Municipalities					
C2	1.67	38.32	61.68	0.74	0.25
N2	7.93	77.43	22.57	0.62	0.22
NE2	1.13	99.12	0.88	0.55	0.17
S2	4.52	32.08	67.92	0.55	0.18
Average	61.74	38.26	0.61*	0.21*	
Average (1, 2)	55.71	44.29	0.76	0.26	

**With the statistical significance at the level of 0.05*

For the composition of HFW, it was found that it was mostly vegetables and fruit scraps, and inedible parts of the plant. This accounted for 27.88% of the total HFW, followed by rice and cereal, inedible parts of animals, meat, noodles and pasta, dairy products, oil, instant food, bakery goods and pastries at 20.79%, 18.21%, 8.73%, 8.52%, 6.60%, 3.77%, and 3.18%, respectively. Other compositions of HFW such as liquids were found to be the least amount at 2.33% of the total, as shown in *Fig. 3*. It was similar to the composition of HFW in Europe and China where vegetable and fruit scraps and plant-based food waste was mostly found (Caldeira et al., 2019; Li et al., 2019).

Fig. 3. *Percentage of the HFW composition in eight studied municipalities in Thailand*



The mixed food waste found in households consisted of protein, carbohydrate (such as starch, cellulose, hemicellulose, and lignin), fat, and organic acid (Xu et al., 2018) which would be difficult to sort and develop into other value-added goods or nutrient products. Most of the food waste was used for animal feed or disposed by the municipalities. Many domestic and international research writings recommend the use of anaerobic digestion of food waste to produce biogas, and other renewable energy to reduce GHG emissions. Also, the residue from the compost could be used as fertiliser to increase soil fertility (Sawain et al., 2021; Hussaro et al., 2017; Koido et al., 2018; Thi, 2017; Pakvilai, 2021). Therefore, if municipalities could collect and sort HFW at the source in sufficient amounts, it could be used to produce energy. Approximately one tonne of mixed food waste could produce as much as 75–140 m^3/wet tonnes of biogas. If biogas was used to produce biodiesel, it could power a car for 852 kilometres, or generate electricity for 0.26 MWh/tonnes which would benefit the environment and create value (Jain et al., 2018). However, the characteristics of the chemical and physical compositions of food waste worldwide are different according to the country's areas or regions, seasons, sources (such as markets, restaurants, households, hotels, schools), as well as social and cultural influences and behaviours (Khair et al., 2019; Maclaren, 2020). It was a challenge thus to determine the appropriate food waste treatment technology with optimum benefit. A study must therefore be conducted on the feasibility of economic, social, and environmental factors of each area. Different waste treatment technologies could be applied including direct use (direct land application, direct animal feed, direct combustion), biological treatment (composting, vermicomposting, anaerobic digestion, fermentation), physicochemical treatment (transesterification, densification), and thermochemical treatment (pyrolysis, liquefaction, gasification (Lohri et al., 2017)).

GHG emission of MFW in eight studied municipalities

From October 2020 to September 2021 (2021 fiscal year), the study showed that the eight municipalities contributed GHG emissions from the collection and transportation of 7538 tCO_2-eq/year, which was less than the 2020 fiscal year at 7728 tCO_2-eq/year due to a decrease in MFW, and as a result, fossil fuel consumption. On the average, for the 2021 fiscal year, the study of GHG emitted only from diesel engines from collect and transport waste to disposal sites showed that C1 and C2 discharged the highest and the lowest GHG with C1 at 4891 and C2 at 16 tCO_2-eq/year as shown in *Table 3*. The study found that GHG emission from collecting and transporting waste had a strong relationship with fossil fuel consumption and the amount of MFW according to the Pearson correlation of r = 0.925 and r = 0.882, respectively. Moreover, the research findings in *Table 4* clearly show that for the MFW management, the process of food waste disposal had an average GHG emission potential of 63,043 tCO_2-eq/year, which was higher than the processes of collecting and transportation. The municipalities undertaking food waste treatment with sanitary landfill processes such as C1, C2, and N1 had GHG emissions from MFW treatment equal to 43,344, 12,416, and 457 tCO_2-eq/year, respectively (*Table 4*). The ratio of GHG emissions for these municipalities per MFW per year was the highest at 0.80, 0.75, and 0.74 tCO_2-eq/tonne/year, respectively, followed by municipalities using incinerators, namely S1 and S2 with 0.59 tCO_2-eq/tonne/year. The municipalities with composting management (NE1, NE2 and N2) generated the least GHG emission per MFW accounting for 0.17, 0.16 and 0.15 tCO_2eq /tonne.

Even though GHG emission of MFW per year from S2 and S1 were not the highest, the GHG generated per capita per year for S2 and S1 were some of the highest with values of 800.16 and 342.53 $kgCO_2$-eq/capita/year. Since S2 and S1 are in major tourist attractions, the number of latent populace can be higher as people come to work, study, and follow their families (Sangkjanan and Auengchaun, 2020). In contrary, the study found that GHG emission of C2 and NE2 was the least per capita per year with values of 3.50 and 8.98 $kgCO_2$-eq/capita/year due to population density and less generated MFW in C2 and NE2. From this study, the GHG emission per MFW per year can represent the potential to manage food waste of the municipalities, while the GHG emission per capita per year can correspond to the awareness of the food waste as well as food waste treatment methods.

Table 3. *Total GHG emission of MFW management in eight studied municipalities relevant to treatment technology in fiscal year 2020–2021*

Municipality	MFW (tonnes/year)			Transportation GHGs (tCO_2-eq /year)			Treatment GHGs (tCO_2-eq /year)			Total (tCO_2-eq /year)		
	2020	2021	Avg.	2020	2021	Avg.	2020	2021	Avg.	2020	2021	Avg.
(1) Urban municipality												
C1	55,013	53,754	54,383	4657	4891	4774	38,761	38,379	38,570	43,418	43,270	43,344
N1	16,491	17,202	16,847	466	464	465	11,620	12,282	11,951	12,086	12,746	12,416
NE1	26,587	25,897	26,242	1735	1586	1661	2898	2823	2861	4633	4409	4521
S1	19,090	5654	12,372	508	344	426	10,641	3153	6897	11,149	3497	7323
(2) Peri-urban municipality												
C2	653	610	631	15	16	15	448	435	442	463	451	457
N2	3719	2894	3307	160	134	147	405	315	360	565	449	507
NE2	515	412	464	22	23	22	56	45	51	78	68	73
S2	5201	1650	3426	166	80	123	2901	921	1911	3067	1001	2034
Total	127,268	108,073	117,672	7728	7538	7633	67,730	58,353	63,042	75,458	65,891	70,675

Table 4. *GHG emission per MFW and per capita per year of eight studied municipalities related to the food waste treatment in year 2020-20201.*

Municipality (FW treatment)	Avg. MFW (tonnes/ year)	Population	Avg. GHG emission (tCO_2-eq/year)			GHG emission per MFW per yr.	GHG emission per capita per year
			Transport	Treatment	Total	(tCO_2-eq / tonnes/year)	($kgCO_2$-eq / capita/year)
C1 (Sanitary Landfill)	54,383	247,671	4774	38,570	43,344	0.80	175.01
C2 (Sanitary Landfill)	631	130,678	15	442	457	0.75	3.50
N1 (Sanitary Landfill)	16,847	77,518	464	11,951	12,416	0.74	160.17
S1 (Incineration)	12,372	21,379	426	6897	7323	0.59	342.53
S2 (Incineration)	3426	2542	123	1911	2034	0.59	800.16
NE1 (Composting)	26,242	27,528	1661	2861	4522	0.17	164.23
NE2 (Composting)	464	8131	22	51	73	0.16	8.98
N2 (Composting)	3307	6609	147	360	507	0.15	76.71
Total	117,672	522,056	7633	60,043	70,676	0.65	135.38

This study of GHG emission was completed using the studies of eight municipalities using the T-Ver methodology (TGO, 2021d) and comparing four food waste treatment methods: landfill, incineration, composting, and anaerobic digestion. Several different studies were applied (TGO, 2016a; 2018b; 2021c; Challcharoenwattna and Pharino, 2018). The study results revealed that food waste disposal using the sanitary landfill was the method that caused the most GHG emission, followed by incineration, and then composting. This was in line with other studies on the subject.

Chuenwong et al. (2022) also claimed that the waste composition is a significant impact on greenhouse gas emission and found that in Luang Prabang, Laos and Nan, Thailand, most of municipal household waste is treated and disposed improperly as in unmanaged landfill, open damp, etc. To mitigate GHG emission from waste, on-site waste sorting can be key method for waste management to achieve net-zero missions. In China, much of food waste produced is disposed of via landfills, processed into animal feed or reprocessed into waste oil (Wen et al., 2016). Gao et al. (2017) indicated that landfill contributed most to consequences of climate change, being approximately ten times greater than other methods. Gao's study recommended that saving food was the ultimate way to lower environmental impact, but also the distance at which waste is transported has a significant impact. Joshi and Visvanathan (2019) concluded that anaerobic digesting was the preferred option than aerobic composting. This treatment method might be a good choice considering the characteristics of the available food waste in Asia along with its primary environmental and economic benefits. For sanitary landfill, this waste treatment would result in anaerobic digestion for food waste and other types of organic waste. The compositions of protein, carbohydrate, and fat in food waste would be digested by microorganisms and broken down into amino acid, sugar, and fatty acid. This would then be converted into hydrogen, ammonia, volatile acids, and finally into biogas with methane at approximately 50–70%, with the rest being converted into 30–50% carbon dioxide (Paritosh et al., 2017; Indrawan and Binekas, 2018). Although the anaerobic digestion method would generate biogas or methane similarly to the landfill method, the digestion process should be a closed system, and the produced biogas could be utilised and used to create power, thermal generation, or incineration. However, a small amount of GHG was released into the atmosphere (Gao et al., 2017; Joshi and Visvanathan, 2019). If methane were captured or collected from the landfill method and used in making power or thermal generation, it could efficiently reduce GHG emissions (Moult et al., 2018).

For MFW management, carbon credit can be a good incentive for trading carbon domestically through the T-VER project to support relevant activities over the long run. Recently, different municipalities in Thailand had applied their activities to the T-VER project and successfully traded carbon to interested organizations. Compared to the agriculture, national energy, and transport sectors, the waste management sector in Thailand has the lowest output of GHG emissions. However, this has steadily increased from 10.83 tonnes of CO_2-eq in 2010 to 12.58 tonnes of CO_2-eq in 2016 (CBI, 2021). Since food waste is a main component of MSW, and a main source of GHG in the nationally, a further reduction of GHG emissions from the waste can be accomplished by effective food waste management. Furthermore, reducing GHG emissions form waste in Thailand is part of the sustainable development objectives and goals of the international climate commitment.

Although it was clear from this study that municipalities could utilise technologies contributing to lower GHG emissions, zero food waste would be the most efficient method to reduce the impact on the environment. Teigiserova's et al. (2020) study proposes a food waste hierarchy that focuses on prevention rather than treatment or disposal according to the 3R principle, and the circular economy leading to optimal use of resources with the least impact on the ecosystem. Moreover, the amount of waste in Thailand exceeds the capacity for waste disposal, and the level of public participation is considered remarkably low (Nakseeharach, 2020). Therefore, it is crucial and urgent to try and beneficially utilise GHG emissions from MFW treatment in urban municipalities as well as tourist destination areas due to their contributing high amounts of MFW. To ensure a beneficial operation of waste management, a feasibility study must be conducted on the economic, operational, administrative, and social aspects. It is crucial and urgent to apply proper treatment for MFW, especially in municipalities where high volumes of GHG emissions are emitted. This includes such regions as urban municipalities and tourist attractions.

Conclusions

From the study, food waste is a main component of MFW. This is detrimental to the environment and other natural sources including natural resource depletion, natural resource contamination, GHG emission, etc. As a result, it poses serious challenges to each country, city, and municipality to cooperatively formulate an appropriate policy and the food waste treatment technology to use. Therefore, this article presents a food waste overview in Thailand by studying the GHG emissions and waste management from eight municipalities. The main results which lead to the development of a food waste treatment policy in municipalities in Thailand are as follows:

1 Food waste disposal with different technologies would impact the amount of GHG emission. Landfill had the most GHG emission potential, followed by incineration, composting, and anaerobic digestion, respectively.

2 Urban and tourist city municipalities would have the highest amount of food waste, as well as a higher food waste per capita than peri-urban municipalities. To manage municipal waste and food waste accurately, collected data as in the study such as waste survey, questionnaires, etc. are valuable for decision making at all levels. Not only correct data, but consistent data collection would also be very crucial for waste management. This data can then be used for appropriate planning and decision-making to create policies, and choosing which waste management technology method would be best for each municipality. This of course depends on geography, budgets, related personal and participation, scale of treatment, accepted technology, etc., of the region.

3 The appropriate treatment technology not only reduces GHG emission, but could also be used for the trading of carbon credit under the Thailand Voluntary Emission Reduction Program (T-VER) of Thailand Greenhouse Gas Management Organization (TGO) to benefit and generate income for the municipality. The municipality can support staff and encourage communities to participate in the T-VER project.

4 Policy for future food waste treatment should determine the organisation framework according to the food waste hierarchy with adherence to the 3Rs principle, the circular economy, and with a focus on the importance of the reduction of GHG as well as promoting the potential at utilising GHG emissions to foster social sustainability. The efficient use of resources could reduce waste production, coupled with collection and disposal systems. The waste management policies for municipalities need to comply with the Twelfth National Economic and Social Development Plan (2017–2021) which sets a target of 75% of total solid waste to be properly disposed of or recycled by 2021. At the same time, the promotion of environmentally friendly products and sustainable production and consumption will need to be addressed (CBI, 2021).

Furthermore, the waste food causes opportunities to raise foster productivity and economic efficiency, food security, to promote resource and energy conservation, and to address climate change. As Thailand is moving towards a carbon-neutral society in 2065, and net-zero emissions in 2090, changes in household waste management are crucial.

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