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ESTIMATION OF GREENHOUSE GAS EMITTED FROM MUNICIPAL SOLID WASTE TREATMENT AND DISPOSAL IN TAIWAN AND ITS POLICY IMPLICATION

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The increasing municipal solid waste (MSW) generation and the options of appropriate MSW treatment technologies are particularly highlighted on its worldwide impact on the global warming in recent times. It is imperative to assess the potential amount of the greenhouse gas (GHG) emission in the design of MSW treatment and disposal system. This study aims at developing an emission inventory of GHG emission from the MSW treatment and disposal system, by firstly using the IPCC's updated methodology and domestic studies for required parameters in Taiwan. The GHG emission rates from respective MSW treatment and disposal divisions are estimated. The methane emission behavior between the first-order decay model and the triangular method is also firstly compared. Accordingly, the MSW treatment and disposal system in Taiwan generated 7,842.6 Gg CO_2 equivalence in 2002, occupying 2.86 % of Taiwanese net GHG emission in that year. The analysis results also indicate that plastic waste, paper waste, and food waste occupies the largest share of GHG emission from MSW treatment and disposal processes. Thus recycling and reducing activities on them should be enhanced for preventing global warming. The results will help the decision-makers associated with GHG reduction and MSW management to make efficient policy strategies.

Key Words : *Greenhouse gas emission, municipal solid waste management, developing country*

1. INTRODUCTION

The anthropogenic economic activities, such as consumption and production, drive all the aspects of people's lifestyle, and have been considered as a key driving force of global environmental problems[1)-4)]. As the lifestyle changes, the increasing municipal solid waste (MSW) generation and the treatment and disposal of MSW, which mainly consists of landfilling, incineration, open dumping and the composting etc, results in enormous detrimental effects on not only the public health but the natural eco-environmental system[5),6)]. Therefore, the options of appropriate MSW treatment technology are particularly highlighted; besides, the technology option should be decided by considering various issues, concerning the cost, environmental impact, social acceptability, and so forth.

Nowadays the global warming is a critical threat for the sustainability of the contemporary life system, and the scientific evidences suggest that global warming is signified by GHG emission from anthropogenic activities[7),8)]. Recently, GHG emission emitted during the MSW treatment and disposal system are of much concern, and is taken into account on the global warming assessment[9)-17)]. IPCC 2006 methodology is applied widely in the holistic assessment of GHG emission by anthropogenic activities, including the estimation of GHG emission from MSW treatment and disposal system[18)]. This methodology estimates GHG emission by categorized emission behavior in terms of detailed emission parameters as well as respective waste composition and quantities.

For developing countries, it is imperative to include the estimation of the potential GHG emission during the MSW treatment and disposal system in the GHG account system, in which GHG emission from MSW treatment and disposal system is seldom considered. Among the MSW treatment process, the biological process (i.e., landfilling) and the thermal process (e.g. incineration) are the most popular all over the world. Namely, carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) is emitted from the MSW treatment and disposal processes. However, hardly any studies have assessed the greenhouse gas emission from the MSW treatment and disposal processes with regard to the existing technologies.

Mainly, previous studies focused on the GHG emission from landfilling, which is the most popular way of waste disposal but meanwhile contributes large methane emission. Methane has a global warming potential approximately 23 times larger than carbon dioxide for 100-years time horizon[18], and thus landfilling has large impact on global warming. In that estimation, the first-order decay (FOD) model, assuming the decomposition of organic matters obeys the first-order reaction, is well acknowledged as a rational method and being applied[11),12),14),18]. Apart from using the FOD model, Kumar *et al.* (2004) proposed a triangular method, in which the methane emission behavior is assumed to release in a triangular manner within 16 years after the waste is deposited. The triangular method can estimate methane emission with less parameter than the FOD model[10]. Mor *et al.* (2006) compared the methane emission by using the FOD model and a modified triangular method by a case study in a landfill site in India[12]. Their empirical results suggested that the modified triangular method produced an approximate but lower estimate than that by the FOD model. In addition, Talyan *et al.* (2007) adopted a delay function of methane, with an assumed 12-year lifetime, in the system dynamics modeling work to project the GHG emission from MSW disposal in Delhi, up to 2025[13]. Up to the present, the FOD model simulating the decomposition of organic matters of MSW is widely adopted in recent studies. However, the FOD model requires large parameters in the estimation, and the triangular method may be a substitute method for the regions where the data is not abundant. Despite some studies calculated GHG emission during landfilling, hardly any studies estimate GHG emission in terms of incineration, which has become a popular technology option in the countries where the landfilling spaces are unavailable.

Accounting for the global warming issues, this study aims to estimate the GHG emission from the MSW treatment and disposal system, by using the IPCC 2006 methodology, with a case study of Taiwan where the economy is growing rapidly and generating large amount of waste generation as well as GHG emission. Through the analysis results, concrete MSW management strategies can be proposed in terms of the reduction of GHG emission. Furthermore, the impact of MSW treatment and disposal under contemporary technology choices on GHG emission would be clearly revealed. Such assessment not only is beneficial for examining the sustainability of MSW treatment and disposal system, but facilitates the recycling and reuse measures on MSW in the context of global warming. This especially requires the continued interest in MSW management system.

2. METHOD

In order to evaluate the GHG emission contributed by MSW treatment and disposal process, IPCC proposed a criteria for estimating GHG emission and revised it in 2006[18]. The revised estimation procedure made detailed calculation for primary MSW disposal processes, and corrected some irrational assumptions in the estimation (e.g., setting the FOD model as default method for estimating methane emission during landfilling). In this study, major treatment and disposal processes, landfilling, biological treatment, and incineration, are taken into consideration. Actually, some pathways of GHG emission are considered in IPCC's guideline, such as wastewater treatment within the MSW treatment and disposal and open burning. Since the amount of MSW treated by these activities is normally little or without official records, they are out of the scope of this study. In the following calculation, the global warming potential over a time horizon of 100 years are assumed 1 for CO_2, 2 for CO, 23 for methane, 296 for N_2O[19].

(1) Methane emission from disposal of MSW

In landfilling process, methane (CH_4) is generated due to the decomposition of organic matters under anaerobic condition. Based on IPCC 2006 methodology, the amount of CH_4 generated can be estimated by the following equation[18]:

$$LMEE_{s,t} = \left[\sum_i LMEG_{i,t} - R_t\right] \times (1 - OX_t) \qquad (1)$$

where $LMEE_{s,t}$ is the overall methane emission in year t (Gg/yr); $LMEG_{i,t}$ is the methane generated by waste fraction i in year t (Gg/yr); R_t is the amount of recovered CH_4 in year t (Gg/yr); OX_t is the oxidation fraction of CH_4 in year t (ratio).

The main mechanism of the decomposition of

organic matters in IPCC 2006 methodology is the inducing of first-order decay function to simulate the decomposition process of degradable carbon in the MSW. In order to calculate $LMEG_{i,t}$, firstly it is necessary to estimate the amount of decomposable organic matters (*DOCm*) in disposed MSW, estimating by Eq. (2):

$$DDOCm_t = WEL_t \times DOC_t \times DOC_{f,t} \times MCF_t \quad (2)$$

where $DDOCm_t$ denotes the mass of decomposable *DOCm* deposited in year *t* (Gg/yr); WEL_t is the mass deposited of MSW discards in year *t* (Gg/yr) on a dry basis; DOC_t denotes degradable organic carbon in year *t*, fraction (Gg-C/Gg-waste); $DOC_{f,t}$ is the fraction of DOC_t that can be decomposed in year *t* (fraction); MCF_t is the methane correction factor for aerobic decomposition of deposition in year *t* (fraction).

The IPCC 2006 methodology emphasizes the "first order decay" principle for the decomposition of $DDOCm_t$, rather than the irrational assumption that the amount of methane emission is proportional to the total amount of MSW dumped within the year[14),18)]. Assuming the decomposition of $DDOCm_t$ is a first-order reaction, the amount of product will be proportional to the amount of reactant. The methane generation is related to the amount of $DDOCm_t$ deposited. Thus the amount of $DDOCm_t$ accumulated in year *t* can be calculated by

$$DDOCma_t = DDOCmd_t + \left(DDOCma_{t-1} \times e^{-\kappa}\right) \quad (3)$$

where $DDOCma_t$ denotes $DDOCm_t$ accumulated in the landfill sites at the end of year *t* (Gg/yr), and $DDOCma_{t-1}$ is its lag term (Gg/yr); $DDOCmd_t$ is $DDOCm_t$ deposited into the landfill sites in year *t* (Gg/yr).

Then $DDOCm_t$ decomposed within year *t* can be calculated by

$$DDOCmdecomp_t = DDOCma_{t-1} \times \left(1 - e^{-\kappa}\right) \quad (4)$$

where $DDOCmdecomp_t$ is the amount of $DDOCm_t$ decomposed within year *t* (Gg/yr); κ is the reaction constant, i.e. $\kappa = \ln(2) / t_{1/2}$ (yr^{-1}), and $t_{1/2}$ is the decaying half-time of $DDOCm_t$, year.

Thus the amount of methane generated can be calculated using

$$LMEG_{s,t} = DDOCmdecomp_t \times F \times 16/12 \quad (5)$$

where $LMEG_{s,t}$ is the amount of methane generated from decomposable matters of waste fraction *s* within year *t* (Gg/yr); *F* is the fraction of methane, by volume, in generated landfill gas (fraction); 16/12 denotes the molecular weight ratio CH_4/C (ratio).

By using Eq. (2) to Eq. (5), methane emitted within a specific year for one waste category can be obtained, and then using Eq. (1), the total amount of methane emission from landfilling of MSW can be obtained and transformed into CO_2 emission equivalence (CO_2 eq.) amount with the coefficient, the global warming potential of methane.

(2) GHG emission from incineration of MSW

IPCC (2006) provided a detailed methodology to estimate the CO_2, methane, and N_2O emission from the incineration process of MSW. Depending on the data attributes, the users can choose appropriate procedures to conduct the estimation. For MSW data on a dry basis, the calculation can be formulated according to the IPCC 2006 methodology Tier 2a[18)].

(a) CO_2 emission

$$ICO_2E_{s,t} = \sum_i \left[\left(WG_{i,t} \times CF_i \times FCF_i \times OF_i\right) \times 44/12\right] \quad (6)$$

where $ICO_2E_{s,t}$ is the CO_2 emission in year *t* from the incineration process of MSW (Gg/yr) for waste stream *s*; $WG_{i,t}$ is the amount of MSW incinerated by composition (on a dry basis), Gg/yr; CF_i is the fraction of carbon in the dry matter (i.e., carbon content) of composition *i*; FCF_i is the fraction of fossil carbon in the total carbon of composition *i*; OF_i is the oxidation factor of composition *i* (fraction); 44/12 denotes the conversion factor from C to CO_2; *i* is the label for MSW composition category, such as paper, food waste, plastic waste, etc.

According to Eq. (6), the amount of MSW discards by composition on a dry basis is required in the calculation.

(b) Methane emission

$$IMEE_t = WG_{incl,t} \times EFM \times 10^{-6} \quad (7)$$

where $IMEE_t$ is the methane emission by incineration in year *t* (Gg/yr); $WG_{incl,t}$ is the amount of MSW incinerated in year *t* (Gg/yr), on a wet basis; *EFM* is aggregate methane emission coefficient (kg-CH_4/Gg-waste); 10^{-6} is the conversion factor from kilogram to gigagram.

(c) N_2O emission

$$IN_2OE_t = WG_{incl,t} \times EFN \times 10^{-6} \quad (8)$$

where IN_2OE_t is the N_2O emission by incineration in year *t* (Gg/yr); $WG_{incl,t}$ is the amount of MSW incinerated in year *t* (Gg/yr), on a wet basis; *EFN* is aggregate N_2O emission coefficient (kg-N_2O /Gg-waste); 10^{-6} is the conversion factor from kilogram to gigagram.

(3) GHG emission from biological treatment of MSW

In some countries, some part of organic waste, e.g., food waste, garden trimmings, etc., is treated by the biological treatment processes, mainly composting, anaerobic digestion, and mechanical-biological treatment. Primarily, methane and N_2O is released in such process. The estimation can be formulated as the followings[18)]:

(a) Methane emission

$$BMEE_t = \sum_j (M_{j,t} \times EF_j) \times 10^{-3} - R_t \quad (9)$$

where $BMEE_t$ is the methane emission in year t from the biological treatment process of MSW (Gg/yr); $M_{j,t}$ is the amount organic waste treated by technology option j (Gg/yr); EF_j is the emission factor for technology option j (g CH_4/ kg waste treated); R_t is amount of methane recovered in year t during the process (Gg/yr).

(b) N_2O emission

$$BN_2OE_t = \sum_j (M_{j,t} \times EF_j) \times 10^{-3} \quad (10)$$

where BN_2OE_t is the N_2O emission in year t from the biological treatment processes of MSW (Gg/yr); $M_{j,t}$ is the amount organic waste treated by technology option j (Gg/yr); EF_j is the emission factor for technology option j (g N_2O / kg waste treated).

3. CASE STUDY

(1) Background of study area

Taiwan is a small island with limited natural resources, but the population density almost achieves the highest level all over the world, 635 capita per square kilometer[20]. After the rising of democratization, industrialization, and urbanization, people's lifestyle and consumers' behavior in Taiwan changed dramatically. As other developing countries, environmental problems increase all over the island rapidly.

Taiwan made a successful economic development in the last decades. However, such development resulted in the depletion of the environmental quality, including the large amount of MSW generation as well as the GHG emission. Meanwhile, Taiwan is one of the dangerous insular zones threatened by the increasing height of the sea-level due to the global warming. As a developing economy, Taiwan has the obligation to reduce its GHG emission although it is excluded of the "Kyoto Protocol". In 2004, Taiwan emitted ranked approximately 21th on GHG emission all over the world, and even the annual per capita GHG emission reached approximately 11.26 tonnes CO_2 eq., ranking 18th worldwide[21]. As one of the world communities, Taiwan has to reduce its GHG emission rate imminently.

Considering the lifestyle changes, the Taiwan Environmental Protection Agency (TEPA) and its previous administrations has executed several countermeasures to control the rapidly growing solid waste generation for both household and industrial waste from 1974[22]. Fig.1 illustrates the official records of domestic MSW generation and discards in Taiwan; the dataset is from 1990 to 2006[23]. In this study, the amount of MSW discards refers to the portion of MSW generation that will be regularly collected and treated by the local municipalities, i.e., the amount of MSW discards is the amount of MSW generation minus its recycled part. In addition, Fig.2 presents the composition of the MSW fractions from 1992 to 2004 on a dry basis. Due to the impact of the policy measures for the reduction on MSW discards as well as the changes in the lifestyle, the series in Fig.2 is ragged with a decreasing trend. In fact, the TEPA implemented many policy measures on controlling the MSW generation and published supportive regulations based on the principles of command and control as well as economic instruments [24), 25)].

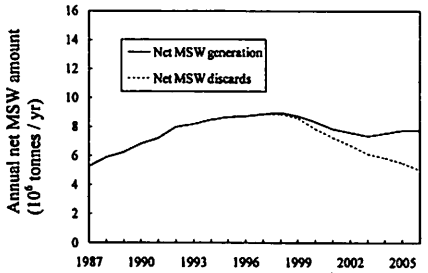

Fig.1 Trends of net MSW generation and discards in Taiwan: 1987-2006.

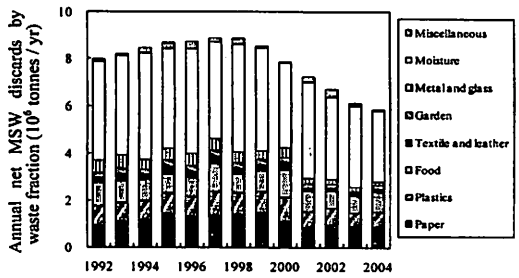

Fig.2 Time series trends of net MSW discards by fraction in Taiwan: 1992 to 2004 (on a dry-basis survey).

On the MSW treatment system in Taiwan, firstly landfilling was comprehensively adopted. However, since the land resources in Taiwan in pretty limited, the TEPA turned the priority of treatment options to incineration after the 1980's. The first incinerator was operated in 1992, and most of planned incinerators were operated during 1998 to 2001, and handled more than 50% MSW discards after 2001. Furthermore, the lately national project set a target that more than 80% of MSW discards will be treated by incineration after 2006[26], and this target was achieved (82.7% in 2006). Fig.3 shows the distribution structure of MSW treatment and disposal system. Noticeably, it is inevitable to choose incineration as the main treatment technology due to the limited land resources in Taiwan. But inefficient

pre-separation of MSW for the incinerators will affect the stability of incineration and even result in emission of hazardous air pollutants such as dioxin and polycyclic aromatic hydrocarbons (PAHs). Thus the TEPA claimed to promote a "zero waste discard" society so that not only resources can be used more efficiently but also relevant air pollution problems can be eliminated[22]. Till date more and more recycling projects are implemented, thus it is expectable that the MSW discards and GHG emission during MSW treatment processes can be reduced.

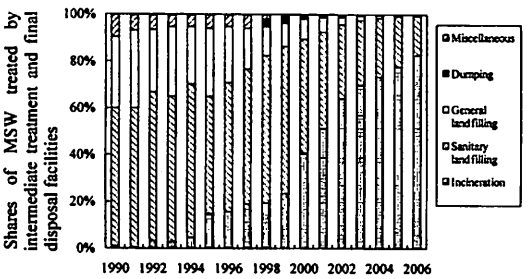

Fig.3 Shares of MSW treated by treatment and disposal facilities: 1990-2006.

(2) Results and discussion

Using the equations discussed previously, GHG emission from landfill and incineration for MSW treatment can be estimated. The emission coefficients used in the calculation are from IPCC 2006 guideline[18], and a domestic study in Taiwan[27].

(a) GHG emission from landfill disposal of MSW

In the estimation of the methane emission from landfill, firstly, methane emission from each waste fraction is estimated by the FOD model using Eq. (2) to Eq. (5). Subsequently the amount of methane emission from the treatment and disposal processes of each waste fraction is adding up to obtain the net methane emission with Eq. (1). Since the MSW composition data was recorded on a dry basis before 2004. Thus, the dry-basis coefficients are used in the estimation. The estimation period is from 1992 to 2004 due to the availability of required data. MCF_i value is set as 1 for sanitary landfill, 0.6 for general landfill site, and the weighted average value is calculated for the estimation[27]; methane recovery is not considered since the equipment for methane recovery is not popular in the landfill sites; the recommended value of OX_i from IPCC is zero; F is assumed as 0.5, the default value in the IPCC's guideline. Parameter setting for the landfilling process is described in Table 1.

Table 1 Typical values of parameters for waste fractions: 1992-2004.

Parameter		Value
DOC_i (Gg-C/Gg- waste)	Paper	0.44
	Food	0.38
	Textile	0.30
	Leather	0.47
	Garden	0.49
MCF_i (fraction)		0.870-0.983
DOC_f (fraction)		0.77
κ (yr^{-1})	Food	0.20
	Others	0.13
$(1\text{-}R_i)$		1
F (fraction)		0.5

Note: a. No methane recovery is assumed in the process, that is, R_i is set to zero.

b. The rational ranges of the DOC_i are (0.44 – 0.50) for paper waste, (0.20 – 0.50) for food waste, (0.25 – 0.50) for textile waste, 0.67 for leather waste, and (0.45 – 0.55) for garden trimmings, respectively.

c. MCF_i is set referring to Yang *et al.*[27] from 0.870 to 0.983; κ is assumed as 0.2 for food waste, otherwise, 0.13; F is assumed as 0.5 based on IPCC's guideline.

In the FOD model, an important coefficient is the reaction constant (κ) in the FOD model, associated with the decaying behavior of waste. This value is affected by the moisture conditions, the degradability of waste, the circumstances disposal sites, etc, rationally ranging from 0.2 for a rapidly degradable material in a warm and wet region to 0.02 for a slowly decomposable waste in a frigid and dry region. Fig.4 demonstrates the decomposition behavior of unit weight of deposited decomposable organic matters (as discussed in Eq. (4) and Eq. (5), deciding the amount of methane emission) under different values of κ, and Table 2 provides its half-life time and duration required to decay 99% of weight under different value κ.

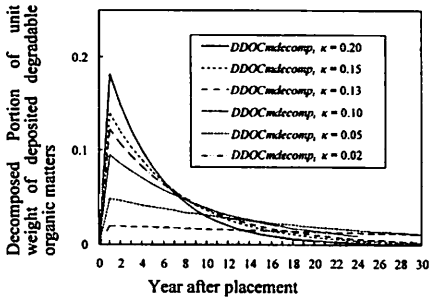

Fig.4 Decomposed portion of unit weight of deposited degradable organic matters.

Table 2 Decaying time of unit weight of deposited decomposable organic matters with different values of reaction constant.

		Half-life time *	Duration required to decay 99% of unit weight of waste*
Reaction constant (κ) (yr^{-1})	0.2	4	24
	0.15	5	31
	0.13	6	36
	0.1	7	46
	0.05	14	92

Note: *Unit: year (after deposition)

From Fig.4 and Table 2, the decomposition behavior of the FOD model would be quite clear, and the results show that the decaying processes are quite different with different κ values. Thus, there is a large uncertainty in deciding the κ value in the estimation. Comparing the triangular method and the FOD model with different κ values, the two approaches would have a similar methane release behavior when κ is approximately 0.13, in which the half-life time of waste are around 6 years after deposition. Since the triangular method is designed on the basis of a tropical Indian case[10], the value of κ for most waste fractions is assumed as 0.13 in Taiwan, where is of a wet and subtropical climate, except for food waste, set as the most rapid rate, 0.2. It should be noted that the FOD model will generate underestimates for the first several years during the estimation period since the GHG emission resulted from the past deposited MSW, which is not available, cannot be accounted in the estimation.

Fig.5 plots the time series trends of the estimates of methane emission (CO_2 eq.) by waste fraction and their shares. The results indicate that paper waste and food waste are responsible for more than 80 % of the net GHG emission from the landfilling of MSW. Intensive reduction measures on the recycling and reuse of paper waste and food waste should be implemented at the perspective of reducing the GHG emission. However, the reuse of food waste, e.g. composting, may become another potential emission source of methane or other GHG in Taiwan, and this part will be discussed in section 3.(2).(c) later.

Moreover, in Fig. 5, the annual net methane emission is decreasing with the rapidly decreasing MSW discards treated by landfilling after 2000 due to the rising tendency of the use of incinerators. The estimates in the first year in the estimation period would be zero. The reason is that the FOD model accounts for the accumulated deposited organic decomposable matters as Eq. (4) shows; however, the missing data in the historical records would produce underestimates of GHG emission when using Eq. (4).

The portion of organic matters in MSW is still likely to decline since the higher incineration rate of MSW is proposed by thenational policy measures in Taiwan, and food waste is separated from MSW discards as one category of the potential resources[22]. Thus a lower net methane emission from the landfilling of MSW may be expected.

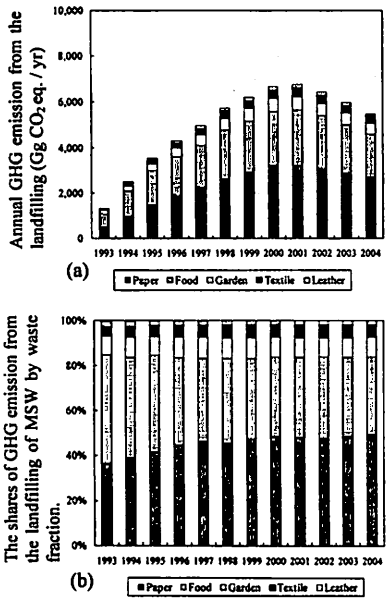

Fig.5 Estimation of GHG emission (CO_2 eq.) from the landfilling of MSW by waste fraction: (a) the amount; (b) the shares.
Note: The estimates in 1992 are zero due to the missing data in the earlier times.

(b) GHG emission from incineration of MSW

Table 4 collects the typical value of parameters referring to IPCC report[18] for performing the estimation from Eq. (6) to Eq. (8). Because MSW discards in terms of waste composition is required in this part, the estimation period is from 1992 to 2004. Fig. 6 shows the results of CO_2, methane, and N_2O emission from incineration process of MSW. In Fig. 6, it is obvious that CO_2 emission occupies much more share than mathane and N_2O emission in the incineration of MSW. Furthermore, the discards of plastic waste contribute more than 90% of the CO_2 emission from the incineration of MSW than other categories. Redunction on GHG emission in incineration can be achieved if plastic waste is reduced through the "3R" principles, e.g., reducing excess consumption on such commodiites, as well as reusing and recycling them during the economic avtivities. However, the food waste does not contribut GHG emission in incineration since the fossil carbon fraction (*FCF*) of food waste is not available in the current references.

Table 4 Typical values of parameters recommended by IPCC in the estimation for incineration process of MSW.

Parameter	CF_i						FCF_i						*EFM*	*EFN*
	Paper	Plastics	Food	Textile	Leather	Garden	Paper	Plastics	Food	Textile	Leather	Garden		
Value	0.46 (0.42-0.50)	0.75 (0.67-0.85)	0.38* (0.20-0.50)	0.50 (0.25-0.50)	0.67 (0.67)	0.49 (0.45-0.55)	0.01 (0-0.05)	1 (0.95-1)	–	0.2 (0.42-0.50)	0.2 (0.2)	0	0.2	47

Note: a. *: recommended value from Yang *et al.*, 2004[27] and is the same as the default value of IPCC 2006 guideline[18].
b. Values in the parentheses represent the rational ranges of the parameter.
c. *EFM* and *EFN* use the value for the stocker-type incinerator.

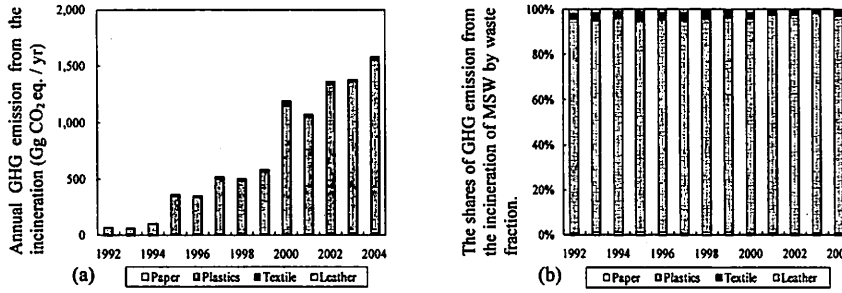

Fig.6 Estimation of GHG emission (CO_2 eq.) from incineration of MSW by waste fraction: (a) the amounts; (b) the shares.

(c) GHG emission from the composting of the recycled food waste

Using Eq. (9) and Eq. (10) with IPCC's default emission coefficients, methane and N_2O emission from the composting of the recycled food waste in Taiwan can be estimated as shown in Table 5. Since the amount of recycled food waste for composting is not large, such GHG emission is much less than that from incineration and landfilling. Though, such calculation is important in a life-cycle perspective.

Table 5 GHG emission from recycled food waste treated by composting: 1992-2004.

Year	M_{Lt} (Gg/yr)	$BMEE_t$ (Gg CO_2 eq. /yr)	BN_2OE_t (Gg CO_2 eq. /yr)	Total GHG emission (Gg CO_2 eq. /yr)
1992	7.855	0.723	0.698	1.420
1993	0	0	0	0
1994	1.370	0.126	0.122	0.248
1995	6.286	0.578	0.558	1.137
1996	2.520	0.232	0.224	0.456
1997	14.173	1.304	1.259	2.562
1998	0.528	0.049	0.047	0.095
1999	19.493	1.793	1.731	3.524
2000	2.782	0.256	0.247	0.503
2001	0.216	0.020	0.019	0.039
2002	3.706	0.341	0.329	0.670
2003	22.290	2.051	1.979	4.030
2004	66.562	6.124	5.911	12.034

Note: a. M_{Lt} denotes the amount of recycled food waste treated by composting.
b. No methane recovery is assumed in the process, i.e., R_t is set to zero.
c. The values of $EF_{composting}$ for methane and N_2O are set as 4 and 0.3 respectively while their rational ranges (0.03 – 8) and (0.06 – 0.6), respectively, on a wet weight basis.
d. The data in 1993 is missing in the official records.

Fig.7 shows the annual CO_2 eq. emission from the main divisions of the MSW treatment and disposal system in Taiwan. As the declining of MSW discards, both CO_2 eq. emissions from incineration and landfilling are diminishing. Moreover, per weight MSW treated by incineration produces less CO_2 eq. emission than by landfilling. Comparing the estimation results and national statistics[23], the GHG emission from MSW treatment and disposal system is approximately 2.86 % of the total CO_2 eq. emission in Taiwan in 2002, while the original national GHG emission inventory was prepared by a different methodology, in which GHG emission from MSW treatment and disposal system was not included.

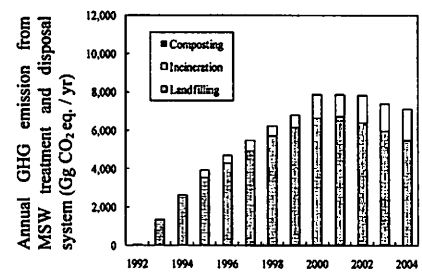

Fig.7 Estimates of annual GHG emission (CO_2 eq.) from MSW treatment and disposal system.

(3) Implication

Tracing back to the purpose of this study, Fig.8 presents the comparison between the accumulated unit GHG emission rates (the accumulated quantities of the annual GHG emission divided by the accumulated quantities of MSW treated up to the current year) by landfilling, incineration, and composting.

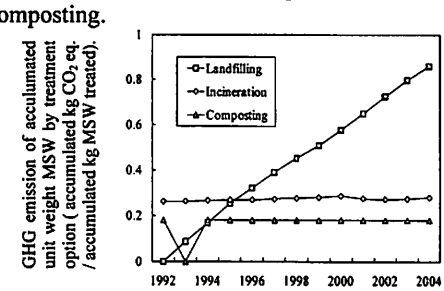

Fig.8 Estimates of acculumated unit GHG emission rate for landfilling, incineration, and composting.

It is obvious that accumulated unit GHG emission rate for landfilling is larger than that for incineration and composting. One reason is that methane, the main GHG released in landfilling, has a 23 times global warming potential larger than that of CO_2, so that the GHG emission from landfilling is enhanced. The methane emission is estimated on the basis of the FOD model, so that high accumulated unit GHG emission rate will be highlighted in the later periods. Besides, the annual amount of MSW treated directly by landfilling is declining to a great extent, enlarging the accumulated unit GHG emission rate for landfilling since methane released accounts for the deposited amount of MSW. In addition, the composting has the lowest accumulated unit GHG emission rate among the three technology options, 0.181 kg CO_2 eq./kg MSW treated. But since the range of the emission factor for composting is quite large (as described in Table 6), more reliable domestic parameters should be developed in the estimation while recommended values are used in this study. The abovementioned results may indicate that the composting and incineration are cleaner technology options from the perspective of preventing global warming. However, more detailed data for MSW composition and characteristics in Taiwan is requireded to conduct the estimation procedure provided by IPCC 2006 methodology, e.g., the methane correct factor (*MCF*), as well as the moisture content, total carbon content ration (*CF*), the reaction constant (κ) in the FOD model, and fossil carbon content ratio (*FCF*) for MSW fractions. Besides, many emission coefficients in the references used the typical values offered by the IPCC guideline, in fact, database of domestic parameters should be established for each countries.

This study focuses on the current treatment and disposal systems, however, potential GHG emission during the reuse and recycling process of MSW fractions should be further considered in the extended study if the data is available. Even, the progress of MSW treatment and disposal system clines to use incineration as the main option of MSW treatment technology due to the limited land resources in some countries, Taiwan and Japan for example. However, such technology option is inconsistent with the argument of "bring back the organic waste to the soil", which aroused more concern in recent studies[16]. From this point of view, organic matters of waste may be treated by composting rather than incineration since the accumulated unit GHG emission rates for incineration and composting are close and much smaller than that for landfilling. However, the optimal technical options should be made by considering the constraints of land resources and administrative budgets, the resource-recycling issues, the optimal GHG emission, as well as the balance of ecologic systems.

4. CONCLUSION

In this study, annual GHG emission from MSW treatment and disposal system in Taiwan is estimated on the basis of the IPCC's revised methodology. The difference between the triangular method and the IPCCs' FOD model is also discussed. Analysis results show that annual CO_2 eq. emission from MSW treatment and disposal system is about 2.86% of total CO_2 eq. emission in Taiwan in 2002. In addition, the analysis results suggest incineration and composting seems to be cleaner technologies in MSW treatment comparing to landfill disposal in the aspect of preventing global warming. Moreover, paper waste and food waste contributes more than 80% of the GHG emission in landfilling, and the discards of plastic waste contribute more than 90% of GHG emission from MSW incineration among the categories. Thus, concrete policy measures in associated with the "3R" principles should be made for reducing the amount of the discards of paper waste, food waste, and plastic waste.

The results presented of the case study in Taiwan show that domestic technological parameters in the estimation of GHG emission are of particular importance in terms of the uncertainty of analysis results. Since most parameters are seldom available except recommended value in IPCC's report, it is necessary for countries to develop domestic values for these parameters so that the estimation would be convincing for domestic assessment, particularly the ratios of moisture content for MSW fractions, which are necessary in the estimation the GHG emission during the incineration of MSW. For the future application, the estimation procedure can be coupled with the forecasting models of the amount of MSW discards so that future projections of the amount of MSW discards and its impact on global warming, the GHG emission, can be evaluated. More concrete and environmental-friendly GHG reduction measures in MSW management system can be considered in a comprehensive aspect. In additional, potential GHG emission during the reuse and recycling activities of MSW fractions, e.g. the composting of recycled food waste, should be further estimated if official database is available.

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