Carbon Balance in Municipal Solid Waste Management-A Case Study of Nonthaburi Municipality, Thailand

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Objective: *This research aimed to investigate the carbon equivalences associated with the unit processes of municipal solid waste management (MSWM) in Nonthaburi municipality. In addition, factors affecting MSWM's carbon-related activities were determined to find the reduction potential of carbon emissions into the atmosphere.*
Material and Method: *A field survey was conducted to quantify the amount of resources used in MSWM. Then, they were evaluated in terms of carbon equivalences occurring in the process scheme and categorized into carbon emissions, fixation and reduction, following a carbon-balanced model.*
Results: *From carbon balance analysis of the base-line-scenario MSWM, the carbon emissions were found to be -2,374.56 MTCE/y, resulting in the average carbon unit of -22.98 kg CE/ton solid waste. The negative sign indicates a carbon reduction, instead of an emission, from this MSWM practice, which helps to reduce the concentration of carbon dioxide in the atmosphere.*
Conclusion: *The results of the model reveal that the highest contribution to carbon reduction potential in MSWM is recycling. Accordingly, it is strongly recommended that a policy promoting reuse, recovery, and recycling be pursued in every step of MSWM to assist in, not only extending landfill service life span, but also alleviating the increasing global warming problems.*

Keywords: *Carbon-balanced model, Municipal solid waste management, Carbon equivalences*

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Municipal Solid Waste (MSW) quantities generated across the country increased from 37,170 tons per day in the year 2000 to 40,082 tons per day in 2006 with the composition of reusable and recyclable materials at over 80%[1]. Nevertheless, the effectiveness of solid waste segregation, including utilization of packaging waste and reusable materials, has not systematically been studied yet. Municipal Solid Waste Management (MSWM) in Thailand is implemented by local government organizations, including Municipality and Sub-district Administrative Organizations. Municipalities take care of urban areas. On the other hand, the sub-district Administrative Organizations take care of the larger areas including agricultural areas with low density populations.

Being an efficient, low cost and easily manageable technology, landfill has become the most popular disposal system in Thailand in response to the Royal Thai Government Policy that every province should have a solid waste management plan[2]. The emission of methane is, nevertheless, a serious threat, which seems to increase if no measures are applied. According to the study of Chiemchaisri et al[3], total methane emissions from the disposal sites nationwide were estimated at 115.4 Gg/y and would increase to 193.5 Gg/y if the existing sanitary landfill is upgraded to integrated waste management facilities. Among all the regions of the country, metropolitan Bangkok has the highest methane emission of 54.83 Gg/y. Some scientists have applied life cycle assessment to MSWM to identify the environmental burdens and to assess the potential environmental impacts[4,5]. Consequently, the net greenhouse gas emissions from MSW incineration and landfilling were reported to be 737 and 1,313 kg CO_2 equivalent/ton of MSW treated, respectively. However, the above method does not classify the origin of concerned material, either fossil or freshly formed organic carbon that causes global warming problems.

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Therefore, understanding the global carbon cycle related to MSWM would encourage more of the public to participate in the reduction of carbon emissions. The potential approach for this is the application of the Carbon Balance Model (CBM) that enables the analysis of carbon flows in terms of the material balance of a given system. The CBM approach being applied in the solid wastes management sector can be used as a template for policy makers to cope with the increasing municipal solid wastes generation. Therefore, this work was carried out with the objectives of (1) to quantify the resources used in the unit processes and factors affecting the carbon emissions in the MSWM activities and (2) to find a potential reduction of carbon emissions.

Material and Method

In order to address the objectives stated previously, the methodology of this study can be set up and divided into four parts: 1) data collection and establishment of a database system, 2) evaluation of carbon equivalent coefficients per unit quantity of solid waste based on the carbon balanced model, 3) evaluation of carbon equivalence, and 4) formulation of carbon balanced equations for solid waste management.

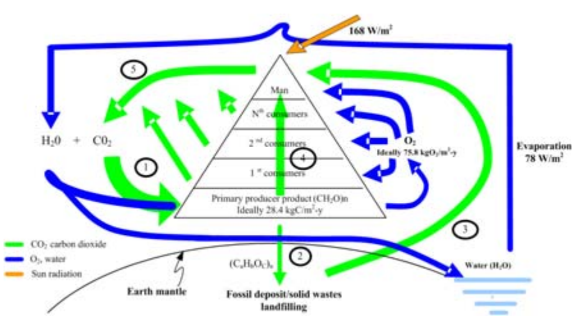

Fig. 1 Conceptual CBM of the globe (modified from Polprasert and Chaiyachet[6]).

Data collection and establishment of a database system

Nonthaburi City Municipality was the selected area for data collection. The data used in this study were both from primary and secondary sources. To evaluate the existing data, the preliminary survey of input material and energy consumption on solid waste management was carried out. Primary data of this research were collected from the site visits and interviews with the concerned municipal officers, who also provided the records of MSWM operations for the past four years. They were used, not only in establishing the database, but also in validating the findings derived from the secondary data.

Coefficients of carbon equivalence

Coefficients of carbon equivalence were calculated, using the concept of CBM modified from Polprasert and Chaiyachet[6] as shown in Fig. 1.

Organic carbon

The coefficients of carbon equivalence from resources containing carbon components with known chemical formula were calculated by dividing the total atomic weight of carbon (n x 12) with the molecular weight of the resource, as shown in Table 1.

Electricity generation

The carbon dioxide emission factor of Thailand's national electricity system in 2007 was 0.561 kg CO_2/kWh with the ratio of C to CO_2 molecular weight of 0.27[9]. Therefore, 0.153 kg CE/kWh is the coefficient

Table 1. Coefficients of carbon equivalence from organic carbon

Resource	Formula	Coefficients of carbon equivalence (kg CE/ kg resource)	Colorific value (MJ/kg)
Diesel at the density of 0.85 kg/m^3	$C_{12}H_{23}$	0.940*	-
Gasoline	C_8H_{17}	0.850	-
Polyethylene**	C_2H_4	0.875	47.74
Polyethylene terephthalate (PET)**	$C_{10}H_8O_4$	0.624	24.23
Polystyrene**	C_8H_8	0.920	43.65
Polyvinylchloride**	CH_2CHCl	0.550	23.31

*(7); **(8)

used to determine the carbon equivalence from electricity generation and/or consumption found in the present study. In general, the electricity consumption from the grid network is considered a carbon emission as the country's major sources of energy for electricity generation come from fossil fuels.

Evaluation of carbon equivalence

Carbon equivalences in the present study are categorized into three, namely: carbon emission, fixation, and reduction to differentiate the groups of carbon utilization that affect the movement of carbon between earth's atmosphere and lithosphere[10].

Carbon emission

Carbon emission is the amount of carbon emitted into the atmosphere when fossil energy and/or fossil-derived materials are consumed or utilized by humans. After this, it remains in the atmosphere as the incremental CO_2.

From the weight of resource usage, the Equation (1) below is used to calculate the carbon emission.

$$C_{em} = C_{coeff} \times W \quad (1)$$

C_{em} is carbon emission (kg CE/ton solid waste).

C_{coeff} is coefficient of carbon equivalence (kg C/kg of resource).

W is resource or energy input (kg or kWh) per ton of solid waste.

Carbon fixation

Carbon fixation is organic carbon freshly formed in photosynthetic reaction. It is then harvested and mobilized horizontally to serve human needs in the form of food, fiber, and fuel. As it originates from the atmosphere after human consumption of carbon fixed, this degradable organic carbon could be transformed either aerobically or an aerobically to carbon dioxide or methane, returning to the atmosphere, resulting in no increase of the atmospheric carbon concentration. However, to satisfy human needs, a suitable and adequate agricultural plantation is definitely required[11].

Carbon fixation of solid waste mass in the system is calculated from the composition of carbon storage in landfill[12].

Carbon reduction

Carbon reduction (C_{re}) is calculated from the recovery and recycling of waste or discarded materials generated from the MSWM. It is called carbon reduction because its implementation helps conserve the natural resources and fossil energy, thereby reducing the amount of carbon originally emitted from the whole manufacture[13].

Formulation of carbon-balanced equations for solid waste management

The total amount of greenhouse gases generated from MSWM activities, as shown in Equation (2), is usually expressed in equivalent tons of carbon dioxide (CO_2) and subsequently converted to carbon by multiplying with C/CO_2 conversion factor (12/44).

$$\text{Net CE} = \Sigma C_{ec} + \Sigma C_{lf} - \Sigma C_r + \Sigma C_{inc} + \Sigma C_{mbt} \quad (2)$$

CE is carbon equivalence of the system MTCE/year

ΣC_{ec} is total carbon equivalence from energy consumption in collection, transfer and transportation of the system. MTCE/year, which is calculated from total Energy (Diesel, Gasoline, NGV and other fossils) consumption in collection (unit/year) x Carbon Equivalence of each energy use (MTCE/unit of energy) MTCE/year

ΣC_{lf} is total carbon equivalence from landfill, which is calculated from "C_{elf}-"C_m-"C_s

ΣC_{elf} is total energy (Diesel, Gasoline, NGV, Electricity and other fossils) consumption in landfill (unit/year) x carbon equivalent of energy use (MTCE/unit of energy) MTCE/year

ΣC_m is carbon from methane production from biodegradable solid waste in landfill site MTCE/year = total mass of biodegradable solid waste composition x CH_4 production rate from landfill for each composition of solid waste (Food waste, paper, some type of plastic, wood and yard waste) x Carbon/Methane conversion factor (12/16)

ΣC_s is total carbon fixation in the landfill that is stored in the landfill. MTCE/year = total mass for each of solid waste composition from the landfill that is not fully decomposed by anaerobic bacteria x the final storage factor of carbon for the biodegradable solid waste components MTCE of CO_2E/Wet Short Ton x C/CO_2 conversion factor (12/44)

ΣC_r is total carbon reduction from recyclable material MTCE/year,which is calculated from total mass of each recyclable material x CO_2 Emission factor for Recycling (MTCO_2E/Short Ton of Material Recovered) x C/CO_2 conversion factor (12/44)

C_{inc} is total carbon equivalence from incineration, which is calculated from

ΣC_{elec} is total carbon equivalence from electricity production, use and sale = Net Electricity x CE conversion factor (1 kWh = 0.153 kg CE)

ΣC_{cf} is Total carbon emission from fossil = Mass of Plastic x CO_2 Emission factor from incineration kg/kg plastic waste x C/CO_2 conversion factor (12/44)

It is noted that carbon emissions from the manufacture of machinery used in MSWM, such as trucks and excavators are excluded from the computation, as they are durable items, capable of handling a much-larger amounts of carbon contained in the solid waste. In addition, the work force employed in MSWM is considered a carbon mobilizer that causes the movement of carbon to satisfy their needs. Hence, it is not included in the calculation of carbon equivalence.

Results and Discussion

Solid waste management in Nonthaburi municipality

With an urban population of 264,485 and a total waste quantity of 96,610.4 tons collected in 2008, the solid waste generation rate of Nonthaburi Municipality was calculated to be equal to 1.0$\pm$0.05 kg/capita-d. The MSW composition is shown in Table 2. Food waste was found to be the major portion with a percentage of 63.55, whereas, plastic, glass, paper, and metal constituted 14.92, 10.21, 4.86, and 1.12%, respectively.

In Nonthaburi Municipality, solid waste collecting trucks collect waste generated from households and haul it to landfill disposal sites. The waste is collected twice a week. The landfill location is 38 kilometers away from Nonthaburi Municipality. It belongs to the Nonthaburi Provincial Administration Organization. The municipality imposes a strategy necessary to reduce the quantity of waste from households with the 3R concept and to monitor waste handling during its transport. As shown in Fig. 2, recyclable materials are segregated from the waste along the management line and sold to recycling shops. In the collection service, there are about 45 waste collecting trucks to serve 107,451 households, and these trucks carry 264.0$\pm$12.9 tons/day of waste to the landfill disposal site. Waste from each household is collected twice a week. Without a transfer station, the collecting trucks go directly to the landfill site after collection. There is no facility to recover methane produced from the landfill site.

Table 2. Nonthaburi Municipality solid waste composition[(14)]

Solid waste composition	% by weight
Food waste	63.55
Paper	4.86
Plastic	14.92
Glass	10.21
Metal	1.12
Rubber/leather	0.32
Cloth	2.07
Yard waste	0.84
Others	2.11
Total	100.00

The total distances were found to be 1,317,600 kilometers for waste collection and transportation with total diesel consumption at 785,049 liters in the inventory year (2008). Therefore, the diesel fuel consumption rate can be computed to be equal to 1.68$\pm$0.03 kilometers per liter of diesel or 7.4E-08 liters of diesel/kg of solid waste/kilometer, resulting in the average of 8.15$\pm$0.50 liters of diesel per ton of solid waste collected.

Carbon emissions from waste collection mainly came from the CO_2 generated by the use of fuel for collection and transportation of waste. The actual emissions varied with the type of truck, fuel type (diesel), size and distances. Total emissions could also be derived from the total distances or fuel usage. As the uncertainty of using distance was higher and collecting trucks also used their engines to power the hopper compactor during solid waste collection and transportation, the total fuel consumption of both collection and transportation was therefore used as the basis for the calculations in the present study. The total amount of carbon emissions from the operation of Nonthaburi MSW collection and transportation was found to be equal to 627,254 kg CE/year and the average carbon emission was 6.51$\pm$0.40 kg CE/ton solid waste.

Carbon equivalence of landfill operations in Nonthaburi MSWM

The schematic flow diagram of mass and carbon transfer for solid waste management of Nonthaburi Municipality is illustrated in Fig. 3.

The equipment used in Nonthaburi MSW landfill consists of: dozers, landfill compactors, track loaders, hydraulic excavators, motor graders, steel wheel rollers, water tanks and trucks. Diesel consumption of Nonthaburi MSW landfill was 195,164 liters/year. The diesel fuel, consumption rate was 2.02$\pm$0.09 liters of diesel/ton of solid waste.

The total amount of carbon emission from

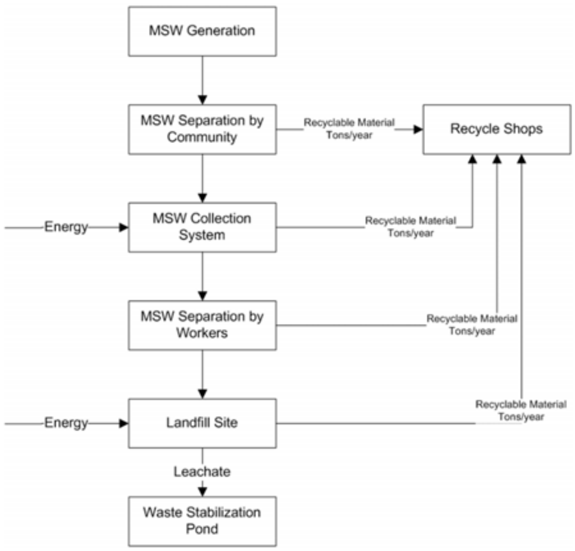

Fig. 2 Flow diagram of MSWM in Nonthaburi Municipality.

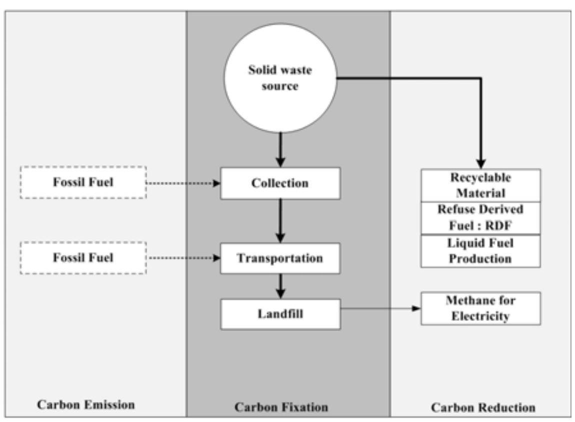

Fig. 3 Schematic flow diagram of mass and carbon transfer in solid waste management of Nonthaburi Municipality.

diesel fuel consumption in the operation of Nonthaburi MSW landfill was found to be equal to 155,936 kg CE/y and the average carbon emission was 1.62$\pm$0.08 kg CE per ton of solid waste.

To estimate the methane generation from the landfill, the computation techniques of IPCC(15,16) were employed. The amount of each composition in the solid waste was multiplied by the conversion factor for food waste, paper, plastic, glass, wood and cloth, which were equal to 99.40, 234.75, 6.57, 3.30, 99.40 and 159 kg CH_4 per ton of material, respectively. It was then converted to carbon equivalence by multiplying with 12/16 (for C/CH_4). The total amount of carbon emissions from the landfill was 5,794.186 MTCE/year or 0.05997 MTCE/ton of solid waste. However, since it originates from biogenic carbon (or carbon fixation), this methanogenic carbon is not counted as carbon emissions, since it returns to the atmosphere.

To estimate the final carbon fixation (storage) in the landfill, factors from EPA's Waste Reduction Model (WARM) for mixed MSW was used. This is equal to 0.22 metric tons of CO2 per wet short ton of MSW multiplied by the amount of wet solid waste in a landfill. The total amount of carbon fixation (storage) in Nonthaburi MSW landfill was 6,389.62 MTCE/y or 0.066138 MTCE/ton of solid waste.

The quantities of the four kinds of recyclable materials-paper, plastic, glass and metals-in Nonthaburi MSWM were found to be 661.78, 94.39, 207.40 and 1,896.39 tons per year, respectively. To estimate the final carbon reduction from the recyclable materials, emission factors for recycling in EPA's Waste Reduction Model (WARM) were used for mixed paper, plastic, glass, and metals, which are equal to 3.51, 1.5, 0.28 and 5.4 metric tons of CO_2 per wet short ton of recyclable material, respectively. They were then multiplied by the amount of wet solid waste in a landfill and converted to carbon equivalence by multiplying by 12/44. The total amount of carbon reduction from recyclable materials was thus found to be 3,157.77 MTCE/y.

Carbon balance in Nonthaburi MSWM

After compiling all inputs and outputs of solid waste, energy and carbon emissions, storage, and reduction in the system boundaries, the next step was carbon investigation of the system. The results of this phase show the contribution of carbon potentials of each processes of Nonthaburi MSWM.

From the model, total carbon emissions came from energy used in the collection and transportation of waste and emissions from work at the landfill. The net carbon emission value was 783.21 MTCE/y. The methane emission from the landfill was 5,794.19 MTCE/y. This amount of carbon is not counted as carbon emissions in the carbon-balanced model because it came from biogenic waste. If the methane was collected and used as a source of energy, it would be counted as a carbon reduction. The carbon storage in the landfill of 6,389.62 MTCE/y was counted as carbon fixation. The carbon reduction came from recyclable material as the reduction sources of 3,157.77 MTCE/y. Therefore, the net carbon balance was -2,374.56 MTCE/y. The negative sign means a carbon reduction. The carbon

Table 3. Carbon balance of Nonthaburi MSWM

Inventory/categories	Carbon MTCE/y			Balance
	Emission	Fixation	Reduction	
Collection				
Diesel consumption	627.25	-	-	+627.25
Landfill				
Diesel consumption	155.94	-	-	+155.94
C /CH_4 Production	-	-	5,794.19*	-
C/Storage	-	6,389.62**	-	-
Recycle				
Paper	-	-	574.71	-574.71
Plastic	-	-	35.03	-35.03
Glass	-	-	14.37	-14.37
Metal	-	-	2,533.66	-2,533.66
Total carbon	783.21	-	3,157.77	-2,374.56

* Not counted as carbon emission; if collected and used as fuel, it means reduction
** Not counted as carbon emission

balance in Nonthaburi MSWM is summarized in Table 3.

Carbon equivalence and waste recycling scenarios

The carbon balance per ton of solid waste in each activity of municipal solid waste management for Nonthaburi municipality is estimated as shown in Table 4. It is found that the majority of carbon emissions came from energy spent in collection, transportation, and land filling; whereas, the major source of carbon reduction is through recyclable materials.

From the model, the total amounts of recyclable materials are increased to 10, 25 and 35% to decrease the quantity of solid waste and carbon emission from energy consumption in collection, transportation, and work at the landfill. As shown in Table 5, the total carbon balance is found to decrease the carbon emissions from -2,374.56 MTCE/y in the base-line scenario to -4,000.04, -4,608.64, and -8,110.91MTCE/y, respectively (Note: the negative sign means a reduction). Also, CH_4 production in landfill is reduced from 5,794.19 MTCE/y in the base-line scenario to 5,697.96, 5,553.61, and 5,475.38 MTCE/y, respectively.

Table 4. Carbon equivalence of activities in Nonthaburi MSWM

MSWM activities	Carbon equivalence (KgCE/ton of solid waste)
Collection	+6.51±0.40
Transfer	-
Landfill	+1.62±0.08
CH_4 Production	59.97*
C-storage	66.14**
Recycle	-31.11
Carbon Balance	-22.98

* Not counted as carbon emission; if collected and used as fuel, it means reduction
** Not counted as carbon emission

Conclusion

The analysis of the Nonthaburi MSWM shows that the net carbon equivalence at the base-line scenario was -2,374.56 MTCE/y with the average unit carbon of -22.98 kg CE/ton solid waste. The negative sign indicates a carbon reduction within Nonthaburi MSWM, which helps to reduce the concentration of carbon dioxide in the atmosphere. The highest contribution to carbon reduction potential is recycling as it can replace products manufactured from virgin resources. Therefore, the carbon emitted from virgin manufacturing processes and the consequent impact potentials can be avoided.

From the scenarios tested, it is suggested that a policy promoting 3R, especially recycling, should be pursued in order to sort out recyclable waste for further human utilization. Other improvements that should be considered in the process of decision-making are landfill gas recovery and waste utilization such as refuse-

Table 5. Carbon balance (MTCE) of Nonthaburi MSWM at various percent recyclables

Inventory/categories	Base-line scenario	Recycle scenarios		
		10%	25%	35%
Collection				
Diesel consumption	+627.25	+622.43	+592.67	+572.83
Landfill				
Diesel consumption	+155.94	+154.89	+147.48	+142.55
C/CH_4 production	5,794.19*	5,697.96*	5,553.61*	5,475.38*
C/storage	6,389.62**	6,323.52**	6,021.18**	5,819.62**
Recycle				
Paper	-574.71	-1,088.00	-1,857.92	-2,371.21
Plastic	-35.03	-876.94	-2,139.79	-2,981.70
Glass	-14.37	-61.54	-132.29	-179.45
Metal	-2,533.66	-2,750.88	-3,076.71	-3,293.93
Total carbon	-2,374.56	-4,000.04	-4,608.64	-8,110.91

* Not counted as carbon emission; if collected and used as fuel, it means reduction
** Not counted as carbon emission

derived fuel and/or compost.

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Potential conflicts of interest

None.

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สมดุลคาร์บอนในการจัดการขยะมูลฝอยชุมชน-กรณีศึกษาของเทศบาลนครนนทบุรี ประเทศไทย

กำพล นันทพงษ์, จงจินต์ ผลประเสริฐ

วัตถุประสงค์: *งานศึกษานี้มีวัตถุประสงค์ที่จะศึกษาปริมาณสมมูลคาร์บอนที่เกิดขึ้นในกระบวนการหน่วยของกิจกรรม การจัดการขยะมูลฝอยเทศบาลในเขตเทศบาลนครนนทบุรี ในขณะเดียวกันปัจจัยที่มีผลกระทบต่อกิจกรรมการ ที่เกี่ยวข้องกับคาร์บอน ได้ถูกประเมินเพื่อหาศักยภาพการลดการปล่อยระบายคาร์บอนออกสู่ชั้นบรรยากาศ*

วัสดุและวิธีการ: *ได้ทำการสำรวจภาคสนามเพื่อประเมินหาปริมาณทรัพยากรที่ถูกใช้ไปในการจัดการขยะมูลฝอย เทศบาล หลังจากนั้น มักถูกประเมินในรูปของสมมูลคาร์บอนที่เกิดขึ้นในกระบวนการ และได้ถูกจำแนกออกเป็น การปล่อยระบาย, การตรึง, และการลดคาร์บอน ตามแบบจำลองสมดุลคาร์บอน*

ผลการศึกษา: *จากการวิเคราะห์สมดุลคาร์บอนของการจัดการขยะเทศบาลที่เป็นอยู่เดิมพบว่า มีการปล่อยระบาย คิดเป็นค่าสมมูลคาร์บอนเท่ากับ -2374.56 MTCE ต่อปี เทียบเท่าค่าเฉลี่ยคาร์บอนต่อหน่วยเท่ากับ -22.98 kg CE ต่อตันขยะ เครื่องหมายลบแสดงถึงการลดคาร์บอน แทนที่การปล่อยระบายจากการจัดการมูลฝอยเทศบาลนี้ ซึ่งจะช่วยลดความเข้มข้นของคาร์บอนไดออกไซด์ในชั้นบรรยากาศ*

สรุป: *ผลของการวิเคราะห์โมเดลพบว่า ส่วนที่มากที่สุดของศักยภาพการลดคาร์บอนคือ การรีไซเคิล ดังนั้นจึงเสนอแนะอย่างยิ่งว่า นโยบายที่สนับสนุนการใช้ใหม่, การนำกลับใช้ประโยชน์, และการรีไซเคิล ควรนำมาใช้ในทุก ๆ ขั้นตอนของการจัดการขยะมูลฝอยเทศบาล เพื่อที่จะไม่เพียงขยายอายุการใช้งานสถานที่กลบฝังเท่านั้น แต่ยังช่วยบรรเทาปัญหาโลกร้อนที่กำลังเกิดเพิ่มขึ้นอีกด้วย*