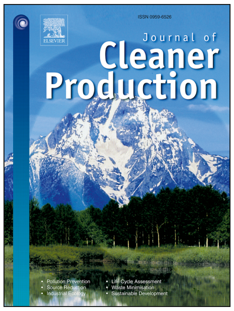


Towards improving emissions accounting methods in waste management: A proposed framework

Amani Maalouf, Mutasem El-Fadel

PII: S0959-6526(18)32726-4

DOI: 10.1016/j.jclepro.2018.09.014

Reference: JCLP 14149

To appear in: *Journal of Cleaner Production*

Received Date: 7 March 2018

Revised Date: 3 July 2018

Accepted Date: 3 September 2018

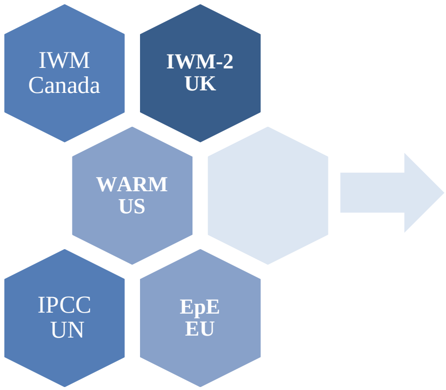
Please cite this article as: Maalouf A, El-Fadel M, Towards improving emissions accounting methods in waste management: A proposed framework, *Journal of Cleaner Production* (2018), doi: https://doi.org/10.1016/j.jclepro.2018.09.014.

Towards improving emissions accounting methods in waste management: A proposed framework

Amani Maalouf, Graduate Student
Department of Civil & Environmental Engineering
American University of Beirut, Lebanon
Bliss Street, Riad El-Solh 1107 2020
Beirut, Lebanon
Email: ahm22@mail.aub.edu

Mutasem El-Fadel, Professor
Department of Civil & Environmental Engineering
American University of Beirut, Lebanon
Bliss Street, Riad El-Solh 1107 2020
Beirut, Lebanon
Email: mfadel@mail.aub.edu
Corresponding author

Emissions Accounting Methods



Common parameters

Operational data

GWP$_{100}$

Time horizon

Default parameters

Type of emissions

Energy produced/consumed

Waste management process

Waste composition

Emission factors

Phase 1

Comparison using default parameters for each method

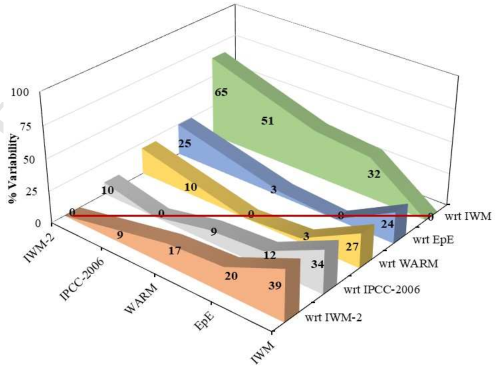
Verification of Emission Factors

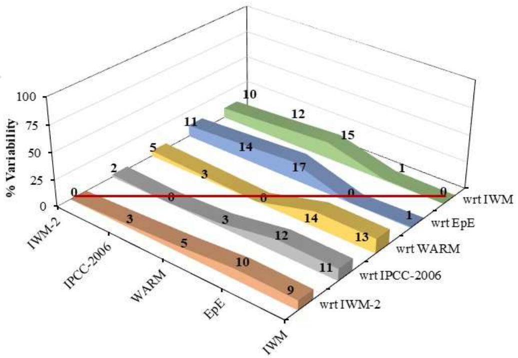
Phase 2

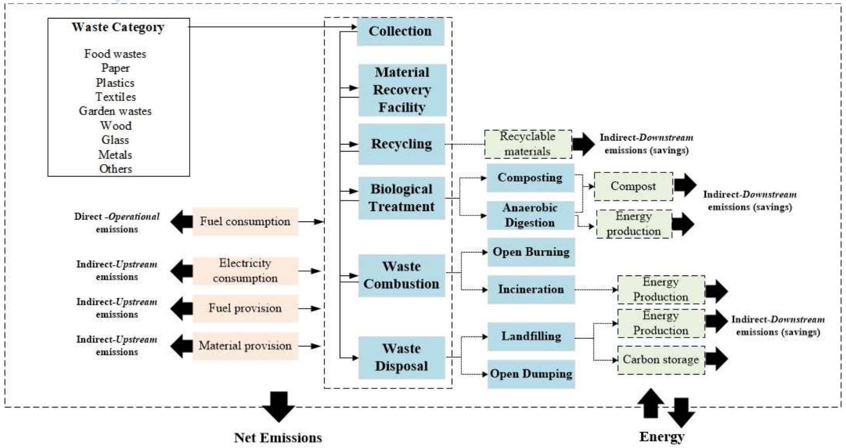
Standardization of parameters in tested methods

Policy Implications & future framework

Emission Reduction Targets & Investments in Carbon Credit







Text including tables and figures captions = 8615 words
Acknowledgements + References = 2217 words

Towards improving emissions accounting methods in waste management: A proposed framework

Amani Maalouf and Mutasem El-Fadel*
Department of Civil & Environmental Engineering, American University of Beirut, Lebanon
* *Corresponding author: mfadel@aub.edu.lb*

ABSTRACT

This study examines the variability in estimating aggregated and disaggregated emissions from the solid waste sector using worldwide adopted methods for country accounting, life cycle assessment modelling, and corporate reporting. Disaggregation of emissions was conducted by source (waste management process from collection to disposal), gas (CO_2, CH_4, N_2O) or type (direct and indirect) to identify processes contributing most to potential variability in estimated emissions. While similar operational data were introduced in all methods, significant variability in estimated emissions were evident across methods. The variability in aggregated emissions ranged from 3 to 65% that dropped to 2 and 17% when default parameters were standardized across methods. At the disaggregated level, a wider variability was discerned reaching several folds depending on the source, gas or type of emissions. The observed variability can be attributed to differences between methods in approaches and default parameters. These differences can affect emissions mitigation measures / reduction targets or influence investments in carbon credit to meet countries' Nationally Determined Contributions under the Paris Agreement. The study concludes with a framework to address limitations in existing methods with emphasis on increased flexibility in allowing the user to modify default approaches and parameters.

KEYWORDS: Waste management; Emissions accounting methods; Carbon credit

1. INTRODUCTION

Concerns about anthropogenic contributions to global warming from solid waste management have stimulated efforts aiming at quantifying and reducing emissions from the waste sector. This practice also referred to as emissions inventorying or accounting or carbon footprint, is dependent on waste treatment and management processes, the type of waste and corresponding physical composition, in addition to the accounting method (Chen and Lin, 2008). In this context, several methods that differ in data requirements and scope have been reported (Gentil et al., 2009) in examining emissions based on specific waste treatment and management processes: 1) the country level accounting with reference to the IPCC; 2) the organizational annual reporting on environmental issues and social responsibility used by corporates, facilities, or municipalities; 3) the LCA modelling as an environmental basis for evaluating waste management systems and technologies; and 4) the carbon trading methodology under the clean development mechanism (CDM). Friedrich and Trois (2011) expressed the need to assess the relationship between these methods and arising emissions from various processes. As such, comparing commonly used methods for estimating emissions from municipal solid waste (MSW) management attracted considerable attention as detailed below in the literature background Section 2 (Table 1). In short, these methods were applied theoretically or for specific case studies to relate their outcomes using default parameters that are invariably dependent on the location where a particular method was developed. In this context, uncertainties are reportedly inevitable when applying any particular method beyond its geographical boundaries (Maalouf and El-Fadel, 2018; Gentil et al., 2010; Friedrich and Trois, 2013; Laurent et al., 2014). This study examines the variability in predicting emissions from MSW management associated with differences in underlying fundamentals and in default parameters including emission factors (EFs). The objective is to define how and what emissions accounting method to use for policy planning and to develop a conceptual framework model to address potential limitations in existing methods. The study compares common emission accounting methods (country level accounting with reference to the IPCC, LCA modelling, and organizational reporting) with a breakdown of emissions into direct operational, indirect upstream, and indirect downstream contributions related to waste management processes from collection to final disposal. We quantify the differences in accounting methods by source (i.e. waste management processes), type of emissions (i.e. direct or indirect), and gas (i.e. CO_2, CH_4, N_2O) while also considering the waste composition. The study provides insights about the variability in emissions associated with various methods and highlights related limitations when applied geographically beyond the context for which they were developed.

2. LITERATURE BACKGROUND

Accounting methods to estimate emissions from waste management have been classified under four main types namely: life cycle assessment (LCA), country accounting, corporate reporting, and carbon credit trading mechanisms (Gentil et al. 2009). The LCA approach is accepted internationally as a standardized method (ISO 2006a, 2006b) to identify, assess, and compare the environmental burdens associated with waste management (Nabavi-Pelesaraei et al., 2017) with many applications in the context of greenhouse gas (GHG) emissions (Table 1) in various countries[1]. The accuracy of LCA tools is strongly dependent on the ability of modeling local conditions and the use of site-specific input data (Ripa et al. 2017). As such, in many countries, the Intergovernmental Panel on Climate Change (IPCC) guidelines (IPCC, 1996; 2006) are still used for national communications under the United Nations Framework Convention on Climate Change (UNFCCC) due primarily to the lack of data required under an LCA approach (Gentil et al., 2009). These guidelines account for direct emissions from the waste sector without consideration to potential inter-linkages with other sectors. Similarly, several protocols and accounting methods were developed based on voluntary industry-led approaches at the organization, facility, corporation, or a municipality level. Whether a mandatory or a voluntary initiative, it is seen as an important contributor to society by reducing GHG emissions from waste management activities. In this context, the Entreprises pour l'Environnemnent (EpE) protocol is widely accepted and was adapted to the waste management industry to account for direct and indirect emissions. As such selecting the proper waste management alternative and estimation method is directly associated with the assessment and mitigation of emissions. The latter is of particular significance in the context of GHG trading schemes that have evolved and reached an advanced stage of implementation[2]. Trading schemes, whether voluntary or regulatory based, have indeed recognized

---

[1] European countries such as Italy (Di Maria et al., 2016; Tascione et al., 2016; Ripa et al., 2017; Rigamonti et al., 2010; Buratti et al., 2015); Denmark (Thomsen et al., 2017); Portugal (Herva et al., 2014); Spain (Quirós et al., 2015; Fernandez-Nava et al., 2014); UK (Evangelisti et al., 2015); Switzerland (Rossi et al., 2015), among others; with limited applications in developing economies such as Turkey (Yay, 2015); South Africa (Friedrich & Trois, 2016); China (Liu et al., 2017a); and other countries in Asia such as Thailand, Kuwait, Bangladesh, and Singapore (Othman et al., 2013), among others.

[2] UK Emissions Trading Scheme (ETS), Chicago Climate Exchange (CCX), European Union Emissions Trading Scheme (EU

the potential of the waste sector for appreciable GHG mitigation. However, these schemes have exhibited wide discrepancies among them, which necessitate consistent accounting procedures to ensure accurate quantification of emissions (Gentil et al., 2009; ISWA, 2009). This can be of importance for country commitment to report regularly on emissions and implementation efforts through nationally determined contributions (NDCs) under the Paris Agreement (UNFCCC, 2015).

In summary, several studies compared these methods and identified differentiating factors such as system boundaries, waste composition, time horizon, energy modelling, and most importantly EFs. However, no study quantified the independent contribution of each factor to the variability in disaggregated emissions by type or source (Table 1). Hence, more efforts are needed in this context towards the development of a framework to address this gap, which is the ultimate objective of this study. The corresponding policy implications of differences in accounting methods can affect mitigation measures and reporting targets under the UNFCCC agreements or influence reduction targets using carbon credits to meet NDCs under the Paris Agreement.

ETS), or the Clean Development Mechanism (CDM) that enables countries with commitment under the Kyoto Protocol to reduce GHG emissions by investing in projects in developing countries to receive in return certified emission reductions (CER) (Maraseni et al., 2010).

Table 1. Past efforts at comparing accounting methods of emissions from waste management

Reference[*]	**Description**
Kulczycka et al. (2015)	Conducted a comparison of several impact categories using two life cycle assessment (LCA) models (generic and specific) applied on a single scenario.
Laurent et al. (2014)	Reviewed literature reported waste-related LCA models commonly used by practitioners.
Friedrich et al. (2013)	Provided a concise synthesis of existing tools, models, and publications deriving and using emission factors in the context of developed countries highlighting their implications when applied in the context of developing countries with the purpose of defining data and methods for a specific study area.
Itoiz et al. (2013)	Presented a technical and operational review of a proposed new tool and compared it with other European tools based on literature reported information.
Karmperis et al. (2013)	Reviewed decision support models that are commonly used in solid waste management while assessing their strengths and weaknesses.
Assamoi & Lawryshyn (2012)	Reviewed existing LCA models to extract data for a case study. Existing models were reported to provide no flexibility to incorporate changes in parameters.
Björklund et al. (2011)	Provided an overview of existing waste-LCA based models.
Eriksson et al. (2003; 2011)	Presented a theoretical comparison of two models to assess their effectiveness in decision-making.
Mohareb et al. (2011)	Compared four emissions estimation methods at a specific case study using default model parameters.
Pires et al. (2011)	Reviewed models illuminating overlapped boundaries in solid waste management (SWM) practices in EU.
Vergara et al. (2011)	Compared two waste-LCA models to assess their differences in emission estimation by considering default model parameters applied on a specific case study.
Cleary (2010)	Reviewed LCAs for SWM systems using 14 computer models emphasizing the need to identifying the scope and methodological assumptions of LCA towards reliable results.
Gentil et al. (2010)	Provided an overview of literature reported LCA models applied to SWM and compared them with respect to technical assumptions, methodologies, and input parameters.
Hanandeh & El-Zein (2010)	Compared simulations using default parameters at a specific case study to validate their developed model.
Del Borghi et al. (2009)	Reviewed existing SWM models and emphasized data constraints (e.g. time-related, geographical, and technological coverage).
Gentil et al. (2009)	Presented an overview analysis and comparison of four main types of emissions accounting methods in SWM. It highlighted the need to examine the relationship between them and SWM processes and technologies.
Rimaityté et al. (2007)	Compared incineration outputs of the LCA model with measured emissions data. Significant differences between simulated and measured data were reported.
Winkler & Bilitewski (2007)	Compared six waste-LCA models using the same waste management scenario and default models' parameters. Significant differences among models were highlighted reaching up to 1400% for some results.
Diaz and Warith (2006)	Model comparison was used in a case study to validate model results, which were then compared to simulations using existing models with their default parameters.
Morrissey & Browne (2004)	Provided a review of existing waste-models and highlighted corresponding shortcomings.
MacDonald (1996)	Provided a detailed review of existing solid waste management-models.

[*] In all studies, the contribution to differences in emissions were not reported and/or quantified independently for each influencing factor.

3. METHODOLOGY

3.1. Comparative assessment approach

Accounting methods for emissions from the waste sector that were tested and compared in this study encompassed the UN IPCC 2006 Guidelines, the US EPA WARM, the EU EpE protocols, the Canadian IWM, and the UK IWM-2 (Table 2). These methods were selected because they are publically accessible, widely reported in the literature, and adopted by cities or countries where they were originally developed (Itoiz et al., 2013; Mohareb et al., 2011; Gentil et al., 2010; Diaz and Warith, 2006). The IPCC guidelines in particular were supposedly put forth to standardize between methods at a global scale. Emissions arising from the waste management scheme involve indirect *upstream* emissions arising from inputs of energy (electricity & fuel) and materials, direct *operational* emissions from systems' operation including onsite operating equipment and waste processing, and indirect *downstream* emissions (or savings) related to energy generation, materials substitution, and carbon storage (Gentil et al., 2009). We emphasize that existing models used in the comparative assessment (Table 2) were selected based on their accessibility and common use worldwide. Other privately-owned models[3] may exist and offer additional features in the context of emissions accounting.

The comparative assessment was carried out under a two-phase approach (Figure 1). In the first phase, the difference in emissions were considered in the context of evaluation criteria (Table 3), which are reportedly of key relevance in emissions accounting from waste management (Gentil et al., 2009), particularly EFs. Additional testing was conducted to verify EFs. This phase entailed calculating the disaggregated and aggregated EFs to validate the variability in the observed emissions at various levels of waste management processes (collection to disposal). In this context, this phase involved

---

[3] Recent privately-owned models such as EaseTech, developed at the Technical University of Denmark (Clavreul et al., 2014) or the Solid Waste Optimization Life-cycle Framework (SWOLF) model (Levis et al., 2013) were not used in the comparative assessment because they have not been endorsed by governmental agencies for compliance purposes although they are useful models for waste management but not commonly reported for planning or decision making. In this study, the comparison targeted methods supported or endorsed by international or governmental organizations, particularly for compliance or GHG emissions reduction purposes.

checking whether the summation of individual EFs multiplied by MSW data characterizing the study area, provides approximately similar outcome as the aggregated EFs. Similarly, direct and indirect contributions were calculated in this additional testing to compare their equivalent disaggregated emissions using a unit category (1 Ton) of a single waste category (i.e. either food, or paper, or plastics, etc.) managed under a single process (collection to disposal). During the second phase, default parameters, particularly EFs, were standardized across methods to ensure a common basis for the comparison while running a single scenario. Following this phase, the methods were compared by source (management processes from collection to disposal) and type of emissions (direct or indirect) with concomitant consideration for waste composition.

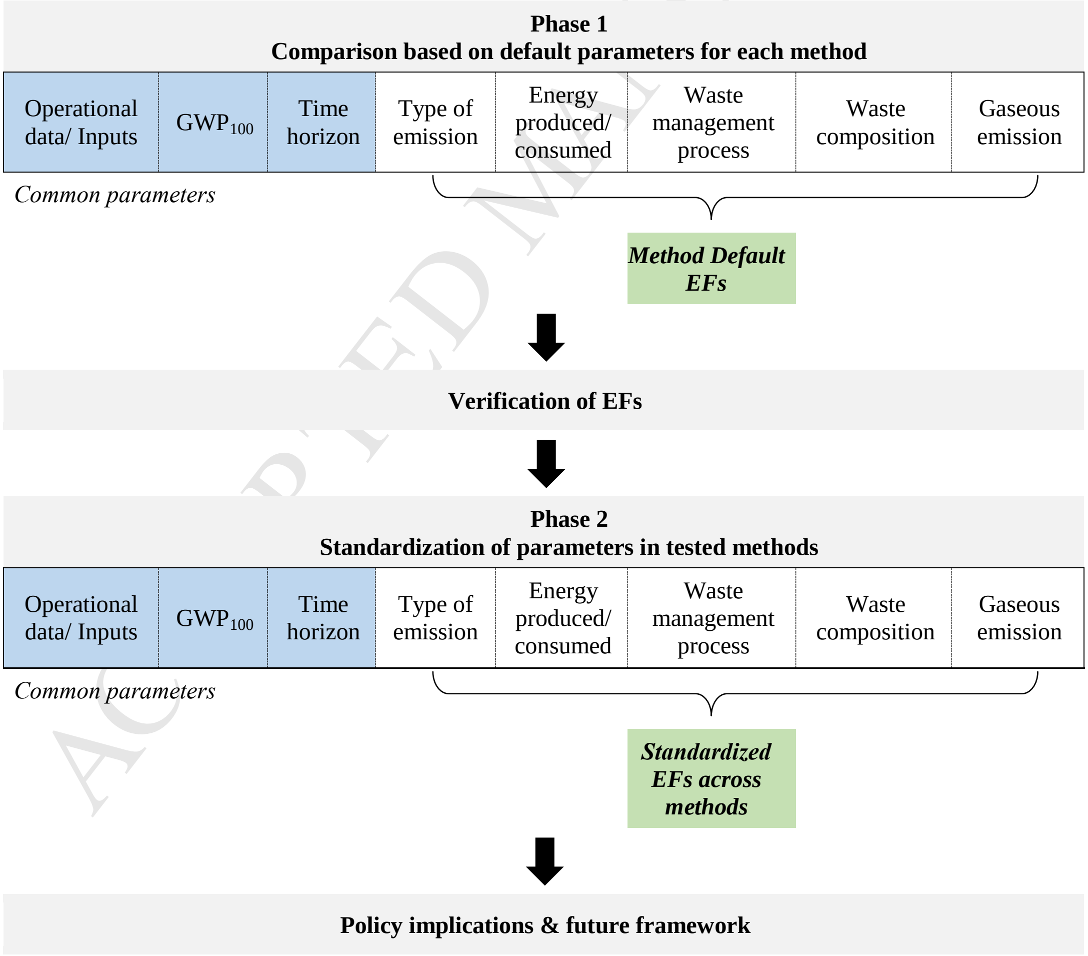


Figure 1. Comparative assessment approach

EFs: Emission factors

Table 2. Characteristics of tested emissions accounting methods

	IPCC 2006	**EpE Protocol**	**WARM**	**IWM**	**IWM-2**
Developed by	IPCC (2006)	EpE (2013)	US EPA/ICF (2012)	EPIC & CSR (2004)	McDougall et al. (2001)
Geographical scope	Worldwide	EU	US	Canada	UK
Intended use	National GHG reporting under the UNFCCC	Enterprise and local government accounting	Technical and environmental platform for decision making associated with municipal solid waste management alternatives		
Scope of accounting	Direct emissions	Life Cycle emissions	Direct & downstream emissions	Life Cycle emissions	Life Cycle emissions
Time consideration	10-50 years	1 Year	1 Year	1 Year	1 Year
GWP_{100} Reference	SAR (1995)	AR4 (2007)	AR4 (2007)	SAR (1995)	SAR (1995)
LF method	FOD	User selected	DM	DM	DM
Source/ sink	Yes/Yes	Yes/No	Yes/Yes	Yes/Yes	Yes/Yes
Management processes	Co, AD, I, Lf, OD	C, R, Co, AD, I, Lf	C, R, Co, I, Lf	C, R, Co, I, Lf	C, R, Co, AD, I, Lf
Waste categories	F, P,P_L, T, W, GA, N, O	Aggregated MSW	F,P,P_L,T, W, GA, G, M, O^f	F, P, P_L, GA, G, M, O	F, P, P_L, T, G, M, O
Emissions	CO_2,CH_4,N_2O	CO_2,CH_4,N_2O	CO_2,CH_4,N_2O	Variable^a	Variable^a
Data requirement	High	High	Low	High	High
Modifiable/ dynamic	No	Yes	No	No	No
Data entry	Waste	Waste/fuel	Waste	Waste/fuel	Waste/fuel
Database/ EFs	Default/ User selected	User selected	Default	Default	Default

(a Includes GHGs (greenhouse gases): CO_2, CH_4, N_2O emissions as well as other emissions such as CO, NOx, SOx, PM, HCl, HF, H_2S, Dioxins/Furans, NH_3, As, Cd, Cr, Cu, Lead, Mn, Hg, Ni, Zn.

IPCC: Intergovernmental Panel on Climate Change; **EpE:** Entreprises pour l'Environnemnent; **WARM:** Waste Reduction Model; **IWM:** Integrated Waste Management Model for Municipalities; **IWM-2:** Integrated Waste Management Model-2; **DM:** Default method (Theoretical yield gas); **FOD:** First order decay method; **LF Method:** method for accounting of methane gas emitted during landfilling; **LC (Life cycle) emissions**: include direct and indirect (upstream and downstream emissions); **EFs:** Emission factors; C: Collection; **R:** Recycling; **Co:** Composting; **AD:** Anaerobic Digestion; **I:** Incineration; **Lf:** Landfilling; **MSW**: Municipal solid waste; **F**: Food; **P**: Paper; **P_L**: Plastics; **T**: Textiles; **GA**: Garden; **W**: Wood; **N**: Nappies; **G**: Glass; **M**: Metals; **O**: others

Table 3. Elements of the comparative assessment of tested emissions accounting methods

Type of Criteria	**Description**	**Example and Standardization**
Scope of accounting	Accounting methods may vary between national GHG inventorying that consider direct emissions (IPCC), and LCA that accounts for both direct and indirect emissions.	Methods were compared by type of emissions: – Direct emissions from waste degradation or from systems' onsite operating equipment. – Upstream emissions from inputs of electricity, fuel, and material. – Indirect downstream emission savings related to energy-electricity generation, material substitution, or carbon storage.
Choice of system's boundary	Accounting methods may consider different waste management processes.	– Example of WARM that incorporates emissions from collection by default to EFs related to simulated processes (e.g. landfilling, composting, etc.), other methods include them under a separate category (e.g. collection). To ensure uniformity, such emissions were credited in all methods as an outcome from waste collection.
Time consideration	Accounting methods consider different reporting timeframe and GWP's time horizon.	– LCA-based methods consider methane emissions over a 100-year time horizon, while the IPCC-2006 adopts a first order decay (FOD). Accordingly, the IPCC-2006 was modified to incorporate a 100-year forecast of emissions. – All methods were set for a single time horizon of 100 years for consistency (GWP_{100}).
Interaction with energy systems	Energy system (consumed or produced) plays a role in the estimation of indirect emissions.	– The default electricity grid and its EF were adjusted for all methods to reflect the study area, which is $688x10^{-6}$ $MTCO_2E/kWh$ (IEA, 2014).
Default data / Other parameters	The methods incorporate default input parameters depending on the location where developed.	– Example about the fraction of landfill gas (LFG) collected: WARM considers a fraction of 0.6 of LFG collected (EPA /ICF, 2016), whereas the actual fraction is dependent on the study area and hence adjusted accordingly in all methods to 0.18 (MoE/UNDP/GEF, 2015).
Biogenic CO_2	The methods consider Biogenic CO_2 emissions with GWP of 0 differently.	– Some methods report them separately while others include them in the accounting of emissions such as IWM that considers biogenic CO_2 emissions during composting. In this study, biogenic CO_2 was excluded from the total emissions for all methods.
Global warming potential (GWP)	The GWP for 100 years' time horizon has evolved with time and the methods adopt by default different GWPs.	– Example of WARM uses IPCC (2007) resulting in 19% increase in GWP_{100} of CH_4, in comparison to IWM-2 (IPCC, 1995) thus the GWP was adjusted in all methods to follow the IPCC reference definition.
Choice of emissions	The methods can consider different gaseous emissions.	– EFs adopted by each accounting method were disaggregated by gaseous emissions (CO_2, CH_4, N_2O, etc. with corresponding GWP).
Waste type and composition	The methods can consider different waste type and composition.	– While some methods consider 7 types of waste categories, others like WARM can consider 45. Moreover, waste components can be managed differently by each method. In this study, the same waste composition was introduced in all methods.
Emission Factors (EFs)	The methods adopt different default EFs.	– EFs were disaggregated by type and source of emissions for each waste category including direct and indirect contributions. During the second phase of the comparative assessment, the same EFs were introduced in all methods.

3.2. Scenario definition and testing

The methods were tested at a pilot area (Beirut, Lebanon) for a comparative assessment of differences and suitability beyond the context in which they were developed. It is worth noting that globally, the contribution of landfilling to CH_4 emissions is ~45% of total emissions from the waste sector (IPCC, 2014). In the pilot area, this contribution reached ~80% (MoE/UNDP/GEF, 2015) highlighting the relative importance of potential carbon credits from the sector at locations with similar characteristics.

The baseline conditions (S0) in the study area consists of commingled MSW collection, sorting and recycling (7%), composting (10%), and landfilling (83%). Waste is collected daily by a fleet of 332 collection vehicles that consume an average volume of diesel equivalent to 6.2 L/Ton of waste generated (Laceco-Ramboll, 2012), which is within reported ranges (Larsen et al., 2009). The waste is then transferred into two material recovery facilities (MRFs) where it is sorted into bulky items, inerts, biodegradable organics, and recyclables. The biodegradable fraction is sent for windrow composting with relatively low-quality compost often rejected by consumers and hence mostly transferred along with other rejects to be used as intermediate cover at the landfill. The collection of landfill gas (LFG) for flaring was initiated partially 4 years after the site opening (at a measured 3 Gg/Year). The number of flares was increased over the lifespan of the landfill to reach 8 continuously operating flaring systems with varied capacities at a measured equivalent of 14 Gg of CH_4 recovered/year in 2013 for potential energy recovery (MoE/UNDP/GEF, 2015). Figure 2 displays the mass and energy sources for all baseline and alternative scenarios while Table 4 summarizes models' input parameters. The two additional scenarios that were considered:

Alternative Scenario 1 (S1): *Collection / recycling / anaerobic digestion / landfilling.* This scenario is similar to the baseline scenario S0, except for replacing the composting process with anaerobic digestion (10%) with energy recovery.

Alternative Scenario 2 (S2): *Collection / recycling / composting / Incineration.* This scenario considers incineration (83%) with energy recovery instead of landfilling in the baseline scenario S0. Note that emissions associated with the management of residues is not considered in all methods except WARM.

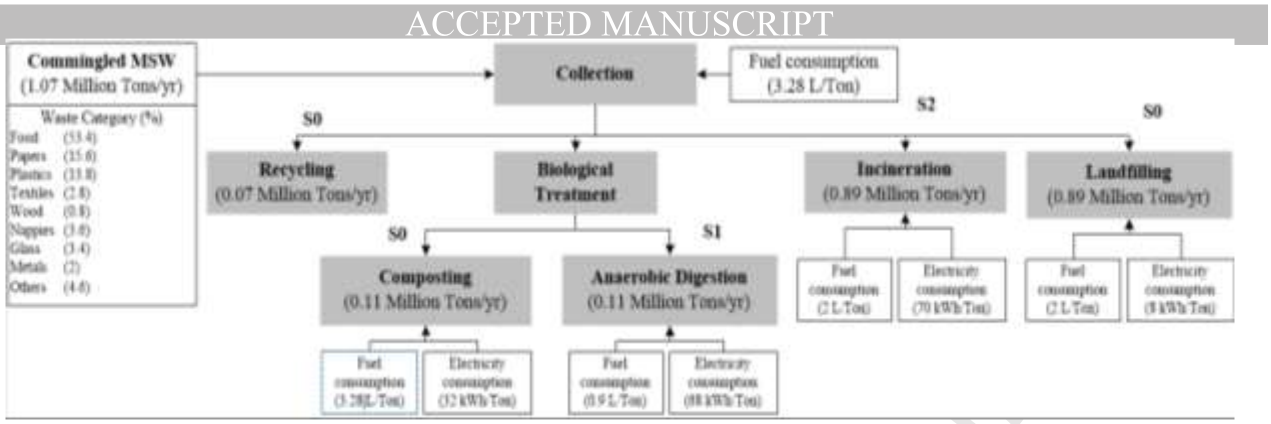


Figure 2. Baseline conditions and scenarios tested at study area
(Data extracted from Laceco-Ramboll, 2012; MoE/UNDP/GEF, 2015)

Table 4. General input parameters

Parameter	Adopted average value	Reference
Fuel consumption for on-site daily operation	~2 Liters/Ton of waste landfilled ~3.28 Liters/Ton of waste composted	1 to 3 Liters of diesel/ Ton of waste landfilled (Manfredi et al., 2009); 0.4 to 6 Liters of diesel/ Ton of waste composted (Boldrin et al., 2009; EPA, 2006; Smith et al., 2001), in most cases an average of 3 Liters/ Ton of waste composted is reported
Provision of electricity	8 kWh/Ton of waste landfilled and 32 kWh/Ton of waste composted	2 to 12 kWh/ Ton of waste landfilled (Manfredi et al., 2009); 8 or 32 kWh/ Ton of waste landfilled or composted (McDougall, 2001)
Fraction of LFG collected	0.18	0.18 at a measured equivalent 14 Gg of CH_4/year in 2013 (MoE/UNDP/GEF, 2015)

4. RESULTS AND DISCUSSION

4.1. Emissions variability

The results using all methods showed that landfilling was the largest contributor to total emissions followed by collection and composting, with recycling contributing to savings in total emissions (Figure 3). Considering each method at a time to be the base for the comparative assessment, the absolute variability in estimated emissions ranged from 3 to 65 % (Figure 4), reflecting the potential change in emissions' reporting using the different methods with their default parameters.

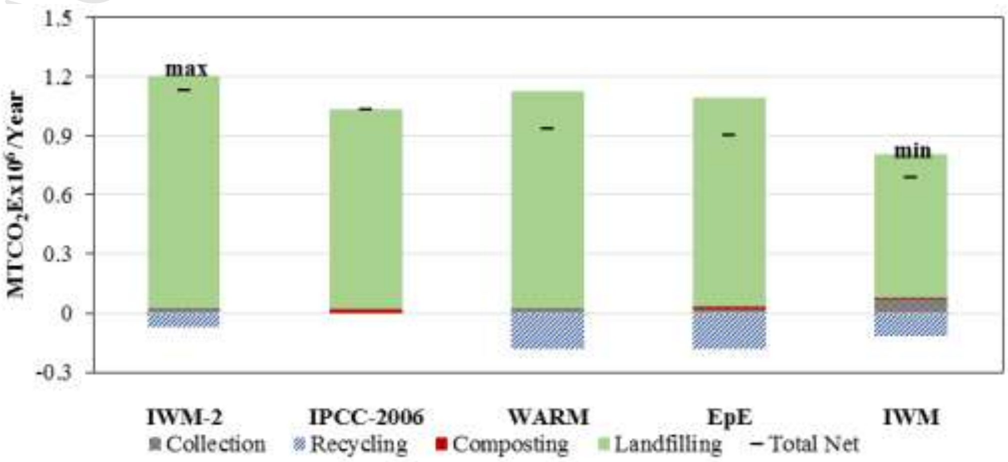
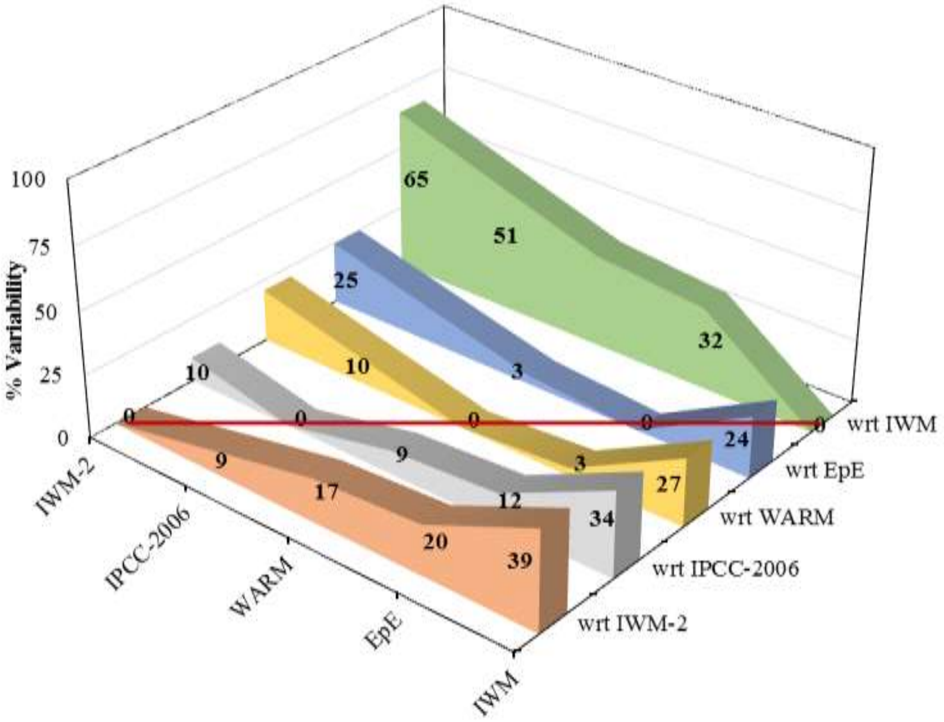


Figure 3. Emissions under baseline conditions (Scenario S0)



	IWM-2 (%)	IPCC-2006 (%)	WARM (%)	EpE (%)	IWM (%)
with respect to IWM-2	0	9	17	20	39
with respect to IPCC-2006	10	0	9	12	34
with respect to WARM	21	10	0	3	27
with respect to EpE	25	14	3	0	24
with respect to IWM	65	56	37	32	0

Figure 4. Absolute variability in emissions with non- standardized parameters
when considering each method at a time to be the base for the comparative assessment
Variability % = | (Value of tested method$_{(i)}$ *- Value of tested method*$_{(j)}$*) / Value of tested method*$_{(i)}$*| x100*

The variability in emissions between methods is detailed in Table 5 by source (waste management process from collection to disposal) and type (direct or indirect) of emissions with values and absolute percent range of differences in comparison to each method. While all methods indicated that the direct emissions from waste degradation and fuel consumption by onsite operating equipment constitute the largest contributor (77 to 93%) to total emissions, a significant variability (3 to 87%) resulted from the usage of various methods (Table 5). Absolute indirect emissions from electricity provision (for composting and landfilling), fuel consumption (for collection or transport), as well as avoided emissions from material recovery (for recycling) accounted for 7 to 23% of total emissions with equally high variability between methods that ranged between 0.3 and 125% (Table 5).

Table 5. Emissions (MTCO$_2$E x 10^6/Year) variability in comparison to each method disaggregated by source and type$^{(a)}$

Emissions	**Waste (Tons x 10^6)**	**IPCC-2006**	**EpE Protocol**	**IWM-2**	**WARM**	**IWM**
Per Source Type						
Collection	1.069		0.018	0.021	0.020	0.070
Difference range %			16-297	14-241	14-241	71-75
Recycling	0.071		-0.187	-0.073	-0.187	-0.118
Difference range %			37-61	62-157	37-61	38-59
Composting	0.111	0.020	0.014	0.001	0.006	0.007
Difference range %		31-93	45-90	414-1283	18-218	15-169
Anaerobic digestion	0.111	0.023	0.005	0.04		
Difference range %		78-80	360-728	45-88		
Incineration	0.887	0.399	0.308	0.88	-0.01	-0.42
Difference range %$^{(b)}$		4-131	16-199	55-67	14-158	4-121
Landfilling	0.887	1.011	1.060	1.179	1.094	0.724
Difference range %		5-28	3-32	7-39	3-34	40-63
Per Type of accounting						
Direct emissions		1.03	1.066	1.18	1.10	0.712
Difference range %		3-31	3-33	7-40	3-35	45-87
Landfilling		1.011	1.055	1.179	1.094	0.711
Difference range %		4-30	4-33	7-40	4-35	42-66
Composting		0.020	0.011	0.001	0.006	0.001
Difference range %		44-95	44-91	11-1643	80-218	12-1852
Indirect emissions$^{(c)}$			-0.162	-0.052	-0.167	-0.029
Difference range %			2-56	120-125	2-55	0.3-55
Landfilling			0.005	0.001		0.013
Difference range %			89-164	838-2374		62-96
Composting			0.002	0.0003		0.006
Difference range %			88-158	731-2041		61-95
Total emissions						
S0$^{(d)}$		**1.030**	**0.904**	**1.128**	**0.933**	**0.683**
Difference range %		**9-34**	**3-25**	**9-39**	**3-27**	**32-65**
S1$^{(e)}$		1.034	0.892	1.120		
Difference range %		8-14	16-26	8-20		
S2$^{(f)}$		0.443	0.148	0.830	-0.135	-0.569
Difference range %		67-228	191-484	40-169	210-715	76-246

(a) The absolute variability in emissions is calculated with respect to each method as follows:
Difference % = |(Value of tested method$_{(i)}$ - Value of tested method$_{(j)}$) / Value of tested method$_{(i)}$| x100

(b) Difference (%) in emissions is calculated based on total emissions excluding avoided emissions from energy recovery.

(c) Total indirect emissions include emissions (savings) from recycling; collection; as well as indirect upstream emissions from landfilling and composting (e.g. electricity and fuel provision)

(d) Scenario (S0): Baseline conditions

(e) Scenario (S1): composting of organic waste in S0 substituted by anaerobic digestion (AD) with energy recovery

(f) Scenario (S2): substituted waste landfilling in baseline scenario by incineration with energy recovery

More significant differences are discerned at the process level particularly composting, anaerobic digestion and incineration due to variations related mainly to default EFs. Process emissions were disaggregated by type of accounting[4] to shed light on differences in the way they are handled in each method (Figure 5). At the disaggregated level, a wider variability was discerned reaching several folds depending on the source, gas or type of emissions.

---

[4] Emissions are categorized by type of accounting as (1) direct (waste degradation and fuel combustion by onsite operating equipment); (2) indirect upstream (e.g. electricity provision); and (3) indirect downstream (or avoided) (energy and material recovery and carbon storage), depending on each waste management method (e.g. collection, recycling, composting, and landfilling).

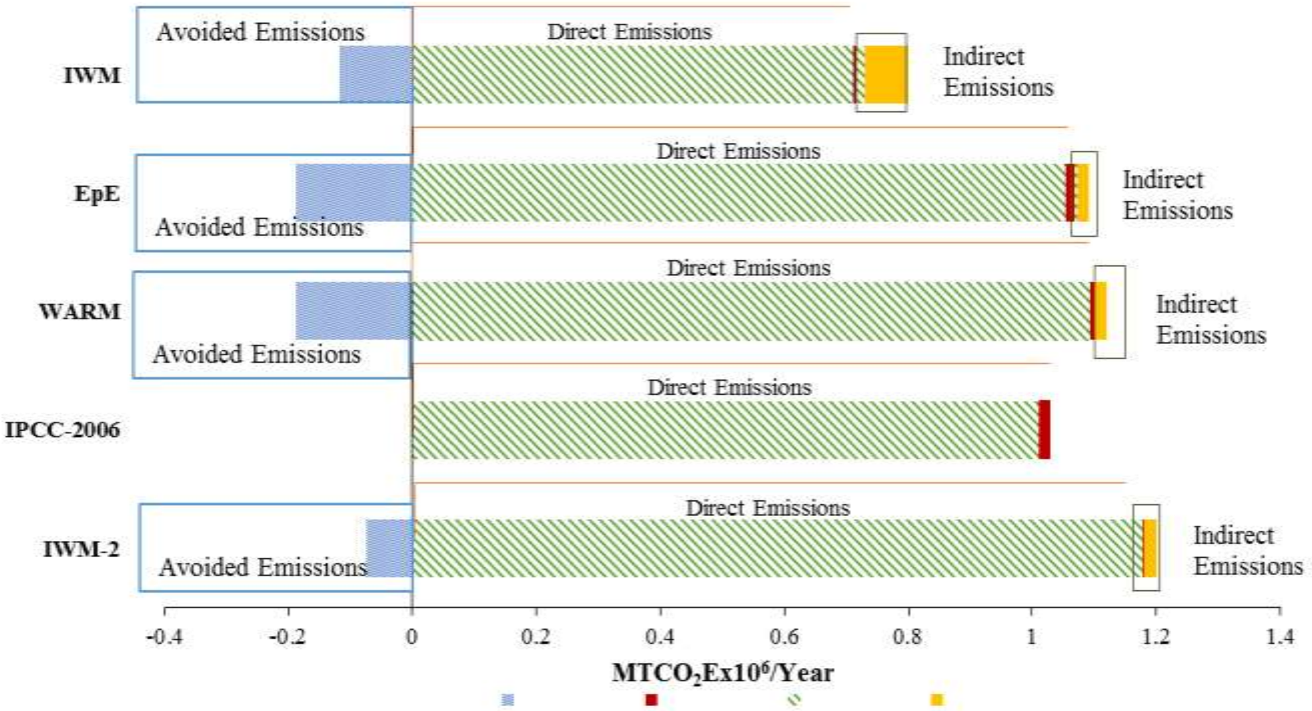


Figure 5. Emissions disaggregated by source and type of emissions for the accounting methods
Direct emissions: *emissions from waste degradation/ processing and fuel combustion by onsite operating equipment;*
Indirect emissions: *upstream emissions from electricity provision;*
Avoided emissions: *indirect downstream emissions from material recovery*

At the *collection and transport* level, IWM-2, WARM, IWM and the EpE protocol account only for direct emissions (during fuel combustion of operating equipment), which varied between methods from 14 to 241% (Table 5), with no consideration for upstream emissions (i.e. fuel provision for the extraction, processing, storage, and transport of fuel). While EpE, WARM, and IWM-2 resulted with comparable total aggregated emissions, IWM resulted in the highest emissions from collection because other methods adopt EFs with 70 to 74% lower values (see Data in Brief article Table 2). IWM considers that the EF of N_2O (~0.007 $MTCO_2E$/Liter of Diesel) are higher than CO_2 (~0.003 $MTCO_2E$/Liter of Diesel) (see Data in Brief article Table 2), which is inconsistent with reported literature that recognizes CO_2 as the major contributor to emissions from fuel combustion during transportation, while N_2O accounts for 2 to 2.8% (Kahn et al., 2007). This explains the increase in emissions from collection and subsequently the high value of total indirect emissions (including savings from recycling) exhibited by IWM in comparison to other methods (0.3 to 55% higher) (Table 5).

Emissions savings from *recycling* consist of the difference in emissions associated with extracting and manufacturing of raw material versus remanufacturing of recyclables. The corresponding emissions exhibited differences between methods from 37 to 157% (Table 5). The EpE and WARM methods adopt similar EFs (EPA/ICF, 2012) and hence have identical savings (Figure 5). In contrast, IWM exhibited lower savings in comparison to other methods. This can be due to its lower adopted absolute EF value of -0.83 $MTCO_2E$ per Ton of paper (see Data in Brief article Table 3), which still falls within the range reported in the literature (-4.4 to 1.5 $MTCO_2E$ per Ton of paper, Merrild et al., 2009), yet, it has a lower absolute saving value than WARM (-3.52 $MTCO_2E$ per Ton of paper). The deviations reflect also the significance of variations in the amount of material diverted to a specific process, which differ depending on the waste distribution adopted in each method. For instance, IWM-2 exhibited the lowest downstream savings from recycling (Figure 5) because by default, it diverts paper waste to composting. Moreover, losses of material during processing, which depend on the efficiency of the sorting process, differ considerably among methods, for instance IWM considers an efficiency of 95% vs. 88% in IWM-2, thus, reflecting differences in emissions.

Biologically, a wide variability in emissions is evident among methods ranging from15 to 1283% (Table 5). For all methods, direct emissions from waste degradation and fuel consumption by onsite operating equipment at the composting facility are higher than indirect emissions from electricity consumption (Figure 5). As a by-product, the compost would offset some CO_2 emissions from fertilizer and peat production or carbon storage from land application (Maraseni and Maroulis, 2008), which are accounted for in WARM only, although relatively insignificant. However, WARM does not consider indirect upstream emissions from electricity and fuel provision (Figure 5). IWM and IWM-2 exhibited the lowest emissions (Figure 5) because they consider CH_4 and N_2O emissions from composting as negligible (see Data in Brief article Table 4) that contradicts the reported literature recognizing them as fugitive emissions produced during the decomposition process (Boldrin et al., 2009; EPA/ICF, 2016; IPCC, 2006).

Substituting composting by *anaerobic digestion (AD) with energy recovery* in scenario S1 decreased emissions in comparison to the baseline scenario (Table 5). IWM-2 exhibited higher emissions than the IPCC-2006 and EpE methods while other methods do not consider emissions from AD. IWM-2 considers that the produced biogas (containing CH_4 and CO_2) also forms CO_2 when CH_4 is burned (McDougall et al., 2001). This produces an equivalent EF of 0.440 $MTCO_2E$ per Ton of wet organic material in comparison to 0.009 $MTCO_2E$ per Ton of wet organic material in EpE, which is inconsistent with the reported literature (Boldrin et al. 2011; Møller, et al. 2009; EPA/ICF, 2016). The other two methods consider fugitive CH_4 emissions due to unintentional leakages (0-10%) during the AD process and CO_2 emissions as biogenic. Also, IWM-2 includes savings from energy recovery whereas the IPCC-2006 guidelines do not account for such savings under the waste sector, thus emphasizing the interdependence of emissions and the interaction with energy systems that is invariably neglected.

The variability across methods in emissions from *landfilling* ranged from 3 to 63% (Table 5). Direct emissions consist of 1) emissions from fuel combustion of onsite operating equipment that are similar in all methods, and 2) emissions from waste degradation processes that differed across methods. While similar operational data are introduced in all methods, the choice of waste composition with corresponding EFs, is different between methods. For instance, the IPCC-2006 considers emissions from certain types of landfilled degradable MSW (e.g. organic, paper, wood, textiles, and nappies) and resulted with 40% higher emissions than IWM (Table 5). IWM considers EFs from landfilled paper and food waste only (see Data in Brief article Table 5). Accordingly, IWM resulted with the lowest emissions amongst the tested methods, with a variability of 40 to 63% (Table 5) with respect to other methods.

Avoided emissions from landfilling include savings from energy recovery that are generally considered by all methods (except IPCC), and savings from carbon storage (considered only in WARM). For the case of the pilot test area, additional savings from energy recovery might not be significant (up to -4%) due to the low efficiency of collected LFG. However, savings from carbon storage, is critical to consider in emissions accounting (Manfredi et al., 2009; Christensen et al., 2009) because it can reportedly cause a significant difference in emissions reaching up to 49% at times (Friedrich and Trois, 2013).

The comparison has also identified a limitation among all methods (except for IWM), which do not account for N_2O emissions from flaring of LFG. In addition, most methods adopt an average of 0.6 for LFG collected (WARM, EPA /ICF, 2016), whereas the actual fraction can be site-dependent as is the case in the study area with a 0.18 value (MoE/UNDP/GEF, 2015). It is noteworthy that none of the tested methods, including LCA-based methods (IWM, IWM-2, and WARM), consider a complete cycle from construction to final closure of a landfill. They tend to rely on databases for large direct emissions from waste, particularly landfill methane emissions without field-validation or consideration to other drivers such as soil cover material, surface oxidation, or gaseous transport (Spokas et al., 2015). These drivers have serious implications for developing a more realistic and science-based landfill inventory.

Substituting landfilling by *incineration coupled with energy recovery* in scenario S2 resulted in a significant variation in emissions (Table 5). This can be attributed to different assumptions adopted in various methods such as the choice of EFs for energy produced or consumed; type of energy sources substituted; energy efficiency; and energy content of waste categories (see Data in Brief article Table 6). This emphasize the interdependence of emissions from waste management systems with energy systems. However, none of the methods accounts for indirect emissions associated with the management of solid residues from waste incineration (e.g. savings from slag recovery and load from bottom ash landfilling) except WARM that considers avoided CO_2 emissions due to recycling of metals recovered from bottom ash.

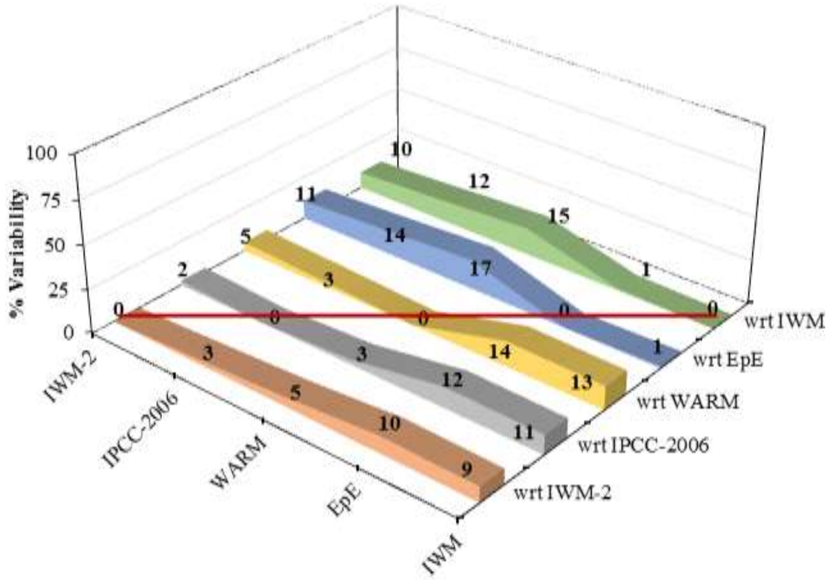
Earlier assessment of several waste-LCA models highlighted the significant differences among models that reached up to several folds for some scenarios (Winkler and Bilitewski 2007). Building up on previous literature findings (Table 1), the above analysis quantified the independent contribution of each factor to the variability in disaggregated emissions by type, gas, and source of emissions. Moreover, it also confirmed that the choice of certain parameters particularly EFs can cause significant differences in emissions accounting emphasizing the need to ensure clarity and flexibility regarding these parameters.

4.2. Verification of emission factors

A cross checking step was implemented to verify EFs and testing results. This phase entailed calculating the disaggregated and aggregated EFs to validate the variability in the observed emissions at various levels of waste management processes (collection to disposal). Aggregated EFs ($MTCO_2E$/ ton of waste) are the cumulative indirect-upstream, direct-operational, and indirect-downstream emissions from treating one ton of waste by individual waste management processes. Disaggregated EFs are expressed in metric tons of CO_2 equivalents ($MTCO_2E$) per characteristic unit (e.g. ton of waste treated; kWh of electricity; liter of diesel fuel). These EFs are separated by waste category, gas, waste process, and type of emissions (direct or indirect). A further illustration of the EFs (disaggregated and aggregated) adopted in each method is displayed in the Data in Brief article (see Data in Brief article Table 7) with corresponding flow diagrams of management systems (see Data in Brief article Figures 1 to 5) that display the energy sources and resulting emissions for each method. The cross checking ascertained the proper application of the tested methods and provided a verification of EFs used within all methods. For example, the disaggregated EFs for composting of food waste using WARM consist of EF related to fuel consumption for the operation of equipment (0.003 $MTCO_2E$/liter of diesel fuel); EF of CH_4 emitted during waste degradation (0.005 $MTCO_2E$/ton of food waste); EF of N_2O emitted during waste degradation (0.041 $MTCO_2E$/ton of food waste); EF related to carbon storage from the application of compost on land (-0.24 $MTCO_2E$/ton of food waste) (see Data in Brief article Table 7). The summation of individual EFs multiplied by MSW data characterizing the study area (Table 4), provides similar outcome as the aggregated EFs of -0.184 $MTCO_2E$/ton of food waste composted (see Data in Brief article Table 7). Moreover, the EFs proved to be the cause of the variability in the overall emissions exhibited by the methods for the same study area and management processes (collection, recycling, composting, anaerobic digestion, incineration, or landfilling); waste category; corresponding mass input; GWP; and similar type of emissions (direct or indirect). In this context, it is imperative while using these methods, to provide a greater clarity in reported emissions, by providing details on related calculations and aggregated EFs particularly in the context of carbon trading.

4.3. Standardization of parameters

The above analysis quantified the range of variability in emissions between the various methods while the second phase of the comparative assessment considered the standardization of all methods. Accordingly, similar operational data and default parameters, particularly EFs were introduced in all methods. EFs were adopted from WARM for all methods and tested for the baseline scenario. EFs from the WARM model were selected because it follows a life cycle inventory approach that includes all direct and indirect processes and accounts for various waste composition. In addition, WARM is the most updated (in terms of energy and emission factors used) among the various methods with the last version 15 released in 2016 (EPA/ICF, 2016) including results from laboratory and field testing. The resulting absolute variability between methods in estimated emissions dropped to 2-17% (Figure 6).



	IWM-2 (%)	IPCC-2006 (%)	WARM (%)	EpE (%)	IWM (%)
with respect to IWM-2	0	3	5	10	9
with respect to IPCC-2006	2	0	3	12	11
with respect to WARM	5	3	0	14	13
with respect to EpE	11	14	17	0	1
with respect to IWM	10	12	15	1	0

Figure 6. Absolute variability in emissions with standardized parameters
when considering each method at a time to be the base for the comparative assessment
Variability % = |(Value of tested method$_{(i)}$ *- Value of tested method*$_{(j)}$*) / Value of tested method*$_{(i)}$*| x100*

A disaggregation of the absolute variability in emissions by source (collection to landfilling) is displayed in Figure 7 to further delineate the difference with respect to each method. While all methods resulted in similar emissions at the waste collection level (Figure 7), after standardization the difference in emissions remained evident at various waste management processes. This can be attributed to default assumptions; the choice of gases (CO_2, CH_4, and N_2O); the choice of waste composition; as well as embedded system boundary conditions whereby certain methods neglect upstream contributions. For instance, the variability in emissions from composting was the highest with respect to IWM (15-107%) and IWM-2 (118-144%) because both methods do not account for CH_4 and N_2O emissions from waste degradation during composting thus resulting in lower emissions. For recycling, all methods (except IWM-2) resulted in nearly similar emissions, which are higher (107-172%) than IWM-2 (Figure 7) because the latter diverts paper waste into composting by default. IWM and IWM-2 account for emissions from paper and food waste during landfilling by default, which resulted with comparable emissions to IPCC-2006 and EpE that consider emissions from food, paper and wood wastes during landfilling whereas WARM accounts for various waste components (paper, food, wood, and mixed waste, etc.).

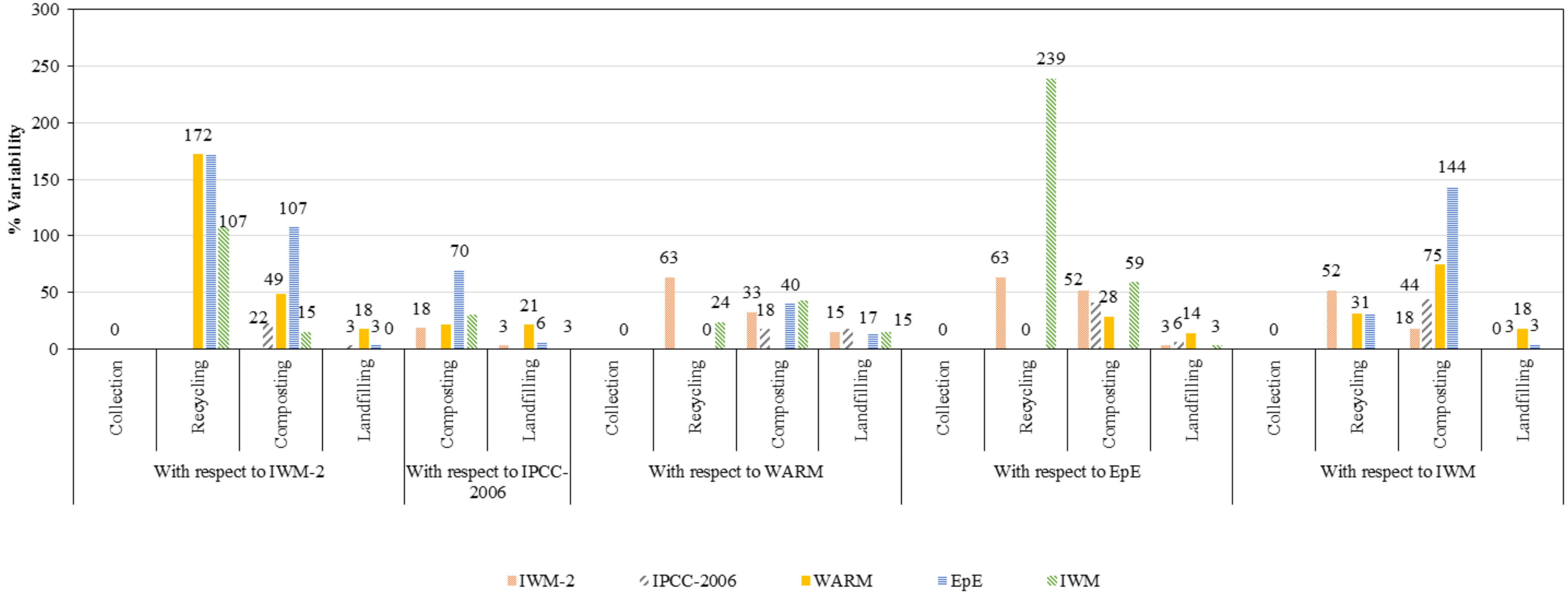


Figure 7. Absolute variability in emissions disaggregated by source
when considering each method at a time to be the base for the comparative assessment
Variability % = $|(\text{Value of tested method}_{(i)} - \text{Value of tested method}_{(j)}) / \text{Value of tested method}_{(i)}| \times 100$

4.4. Summary comparison

The comparative assessment defined several limitations in existing methods mainly at the level of neglecting upstream (e.g. fuel/energy and material provision) or downstream (e.g. avoided emissions from carbon storage and material recovery) processes. In addition, some methods do not address emissions from certain waste management processes such as flaring of LFG collected from landfilling or open dumping and burning. While the latter are improper, they remain common practices in developing economies where a high fraction of the waste is still disposed of in open dumps, or openly burned, or landfilled with an inefficient LFG collection and flaring system (Devkota et al., 2012). Furthermore, most methods were applied in developed economies with default data for respective countries and a lack of flexibility with regards to modifying input parameters as they are not readily accessible or adjustable. The latter is coupled with a difficulty to disaggregate emissions based on the scope of reporting whether for national inventorying (direct emissions) or for LCA (direct and indirect) decision-making and planning purposes. While existing accounting methods consider many direct and indirect contributions, most (except for EpE) do not consider emissions by type (direct vs. indirect). Similarly, most methods neglect downstream contributions with the exception of the WARM model that accounts for offset of CO_2 emissions from fertilizer and peat production or carbon storage from land application of compost, and savings from carbon storage during landfilling. In addition, existing methods (except for WARM) do not account for indirect emissions associated with the management of residues from waste incineration (savings from material recovery and load from bottom ash landfilling). Similarly, all methods do not take into account auxiliary fuel needed to satisfy the low heating value (LHV) during incineration as well as indirect emissions related to the construction of a landfill.

All methods targeted developed economies with default input data introduced for specific locations and often with uncertainty about emission factors that as stated above, are not readily accessible or adjustable (Assamoi and Lawryshyn, 2012; Laurent et al., 2014). Arguably, the IPCC guidelines were developed to address these shortcomings, but these guidelines do not consider emissions savings from waste recycling and do not account for emissions from the collection of waste within the waste sector.

The latter are embedded within the transport sector under energy and must be redirected under the waste sector for comparative purposes of emissions reduction targets and potential carbon credit from this sector. More importantly and due to lack of area-specific input data particularly EFs, the application of the IPCC guidelines has relied on borrowing such data from other locations, mainly developed economies, thus undermining the very purpose for which they were developed in the first place.

While it might be evident that methods with different scope of accounting will likely generate different emissions, the variations were equally significant for methods having similar accounting scope such as LCA-based methods. The variability can be attributed to how several influencing factors are controlled including system's boundary assumptions of waste management processes, the choice of gases and EFs[5], as well as input data and parameters used to describe the MSW management system or using different waste and gas categories for composition[6] and type of emissions[7]. Some of these factors are also related to geographical conditions (electricity generation and fuel consumption with corresponding EFs) while others are related to the equipment performance (efficiency factors). Concurrently, the results underline the interdependency of emissions and the amount of material applied to a specific process, which may differ with the default waste stream[8] adopted by various methods.

4.5. Policy implications and future conceptual framework

At the policy planning level, the relationships between the quantification approach (or emissions accounting method) and carbon credit from waste management, can be schematically represented by Figure 8 where parameters adopted in quantifying emissions from waste management can affect carbon credits when assessing emissions mitigation, reduction targets, or NDCs under the Paris

---

[5] The choice of gases and corresponding emission factors affect the results significantly, for example, IWM resulted in the highest emissions from collection and indirect emissions among methods because it considers that N_2O emissions are higher than CO_2 emissions during fuel combustion.

[6] For instance, while WARM (following EPA guidelines) considers a wide variety of waste categories and accounts for corresponding EFs, the IWM and IWM-2 methods consider EFs for < 5 categories.

[7] For example, IWM and IWM-2 neglect CH_4 and N_2O emissions from composting

[8] Although the same input of waste material was introduced in all methods, the amount of material diverted to a specific process differs depending on the waste distribution adopted in each method. For instance, in IWM-2, paper waste is diverted to composting by default.

Agreement.

Despite many voluntary and carbon market driven initiatives in developed economies, developing countries did not have mandatory obligations for reducing emissions under the Kyoto Protocol. The situation has changed following the Paris agreement (UNFCCC, 2015) whereby it became mandatory for all parties to report regularly on their emissions and implementation efforts through NDCs that incorporate attempts by each country to decrease national emissions and adapt to climate change impacts.

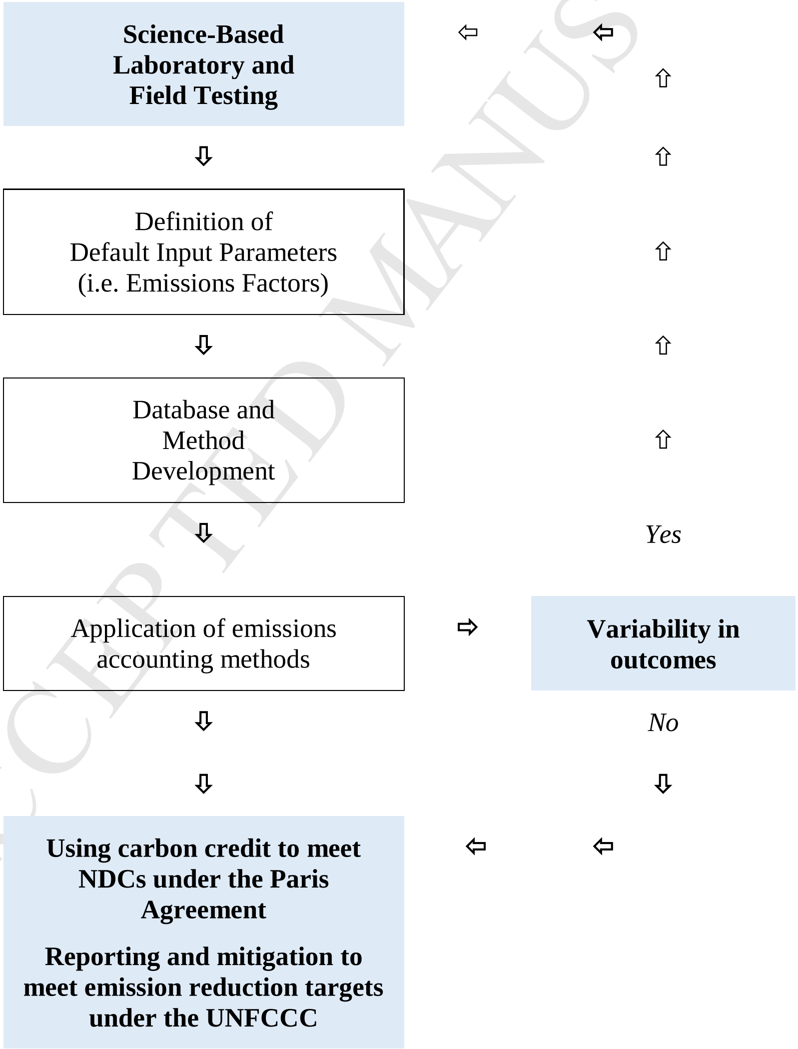


Figure 8. Impact of emission quantification in the context of
using carbon credit to meet NDCs under the Paris Agreement or emissions reporting and mitigation under the UNFCCC
NDCs: Nationally Determined Contributions; **UNFCCC**: United Nations Framework Convention on Climate Change

In this context, it is imperative to develop a well conceptualized and designed tool to harmonize and validate non-geographic assumptions towards strengthening modelling efforts with applicability to both developed and developing economies. Equally important, emissions accounting and reporting methods should include similar data that can then be used differently depending on the scope of reporting whether for national inventorying, LCA modelling purposes for planning and decision-making purposes, corporate reporting, or emission reduction targets using carbon credit. It is also necessary to consolidate the reporting of emissions under existing methods, by providing a single framework such as the Upstream-Operating-Downstream approach (Gentil et al. 2009) to improve accuracy and robustness in reporting background data. Such a framework would build on existing emissions accounting methods with the aim of adding uniformity amongst methods by confirming clarity and traceability for the waste management data. Consequently, this will increase the credibility of mitigation initiatives in the waste management industry and demonstrate its commitment to climate change actions.

Accordingly, a conceptual framework model (Figure 9) was developed to address limitations discerned in this study (Table 6). The proposed framework can accommodate general and specific locations equally with input data from both developed and developing economies defined more explicitly all while offering users the flexibility of modifying input parameters in contrast to a closed source code. Last but not least, the proposed framework encompasses the ability to simulate emissions from a wider range of waste management processes. We re-emphasize that tested methods in the comparative assessment were selected based on their accessibility, common use worldwide, and sponsorship / approval by cities or countries where they were originally developed.

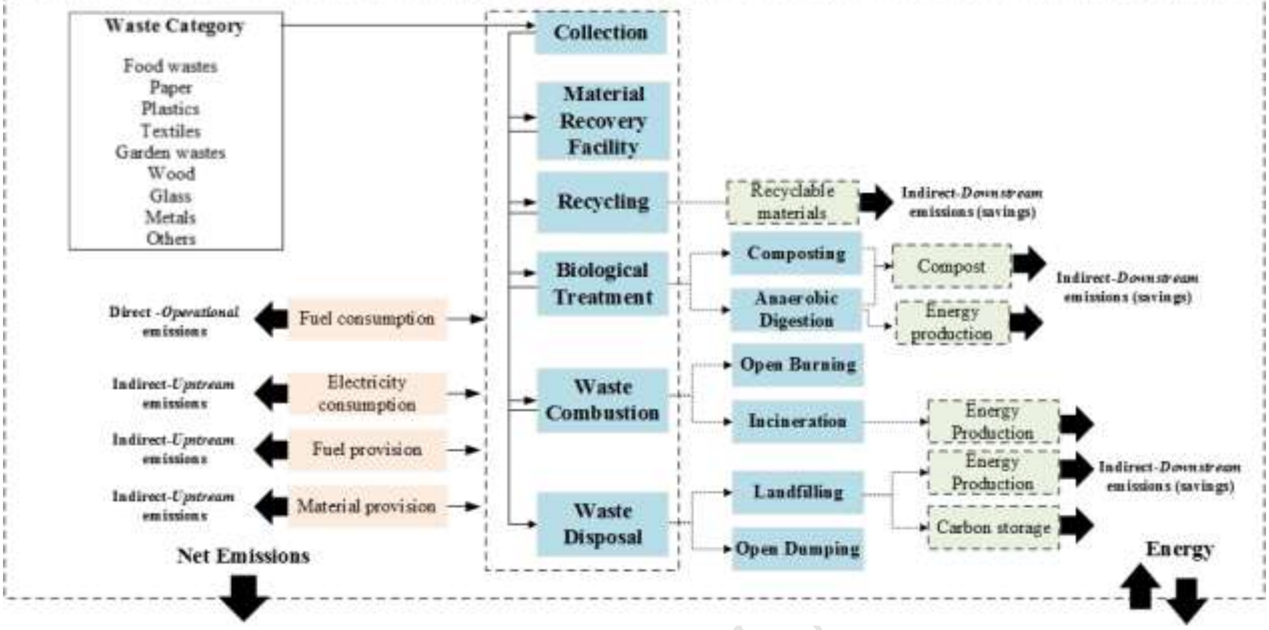


Figure 9. Proposed conceptual framework

Table 6. Comparison of proposed conceptual framework model with existing methods

		IPCC 2006	WARM	EpE	IWM	IWM-2	Framework
Database		Default	Default	User selected(a)	Default	Default	User selected(b)
Modifiable/ dynamic		N	N	Y	N	N	Y
Select emissions by type (c)		N	N	Y	N	N	Y
Select EF/input parameter		N	N	Y	N	N	Y
Select by gas type		Y	N	Y	Y	Y	Y
GWP_{100} Reference		N	N	N	N	N	Y
Collection/transport	*Fuel combustion*	N	Y	Y	Y	Y	Y
	Fuel provision	N	N	N	N	N	Y
Biological treatment	*Waste degradation*	Y	Y	Y	Y	Y	Y
	Fuel combustion	N	Y	Y	Y	Y	Y
	Electricity consumption	N	N	Y	Y	Y	Y
	Fuel provision	N	N	N	N	N	Y
	Carbon storage	N	Y	N	N	N	Y
	Peat substitution	N	Y	N	N	N	Y
	Energy recovery	N	Y	N	N	Y	Y
Incineration process	*Waste combustion*	Y	Y	Y	Y	Y	Y
	Electricity consumption	N	N	Y	N	N	Y
	Energy recovery	N	Y	Y	Y	Y	Y
	Material recovery	N	N	N	N	N	Y
	Fuel combustion	N	N	Y	N	N	Y
	Fuel provision	N	N	N	N	N	Y
Landfill processes	*Waste degradation*	Y	Y	Y	Y	Y	Y
	Fuel combustion	N	Y	Y	Y	Y	Y
	Electricity consumption	N	N	Y	Y	Y	Y
	Fuel provision	N	N	N	N	N	Y
	Material provision	N	N	N	N	N	Y
	Carbon storage	N	Y	N	N	N	Y
	Energy recovery	N	Y	Y	Y	Y	Y
	N_2O from flaring	N	N	N	Y	N	Y
Assessments	*Carbon Credit*	N	N	N	N	N	Y
	Economic	N	N	N	N	Y	Y
	Social	N	N	N	N	N	Y

IPCC 2006: Intergovernmental Panel on Climate Change 2006 Guidelines; **WARM:** Waste Reduction Model; **EpE:** Entreprises pour l'Environnemnent; **IWM**: Integrated Waste Management Model for municipalities; **IWM-2:** Integrated Waste Management Model-2.

(a) In order to calculate direct emissions from waste degradation in landfills, the user selects a common methodology and refers to the regulatory methodologies recommended by the authorities of the country where the site is located.

(b) Ability to disaggregate emissions based on scope of reporting whether for national / GHG inventorying or for LCA / planning and decision-making purposes.

(c) Type of emissions: indirect-upstream, direct-operational, and indirect-downstream contributions (direct and indirect).

5. CONCLUSION

This study examined the variability in aggregated and disaggregated emissions from waste management when using commonly adopted international methods (the UN IPCC 2006 Guidelines, the US EPA WARM, the EU EpE protocols, the Canadian IWM, and the UK IWM-2). The results reflect a persistent variability across methods in estimating emissions whether in total (aggregated), or by disaggregated sources (waste management process from collection to disposal), by gas or type (direct and indirect). All methods rely on default parameters that are invariably not representative of characteristics encountered beyond the geographic location where the method was originally developed. The IPCC guidelines were intended specifically to address this limitation nevertheless key parameters remain largely not available for most countries with a common trend to still use those reported at locations with different characteristics. In addition, the IPCC guidelines that are advocated as a common international ground under the UNFCCC, still do not consider direct and indirect contributions from upstream or downstream processes within the waste management sector. This highlights the need for 1) developing key parameters when lacking with less reliance on those reported beyond the location under consideration; and 2) increased flexibility in accessing and changing default parameters to represent a wider context while accounting for direct and indirect contributions. A conceptual framework was developed to address the latter limitation and provide an improved future tool for assessing emissions reporting targets under the UNFCCC commitments or guiding decision making and reduction targets using carbon credit to meet NDCs under the Paris Agreement.

ACKNOWLEDGEMENTS

This study is supported through a joint funding from the National Council for Scientific Research (NCSR) and the American University of Beirut (AUB). Special thanks are extended to Dar Al-Handasah (Shair & Partners) for its support to the graduate programs in Engineering at AUB.

REFERENCES

- Assamoi, B., Lawryshyn, Y., 2012. The environmental comparison of landfilling vs. incineration of MSW accounting for waste diversion. Waste. Manage. 32, 1019–1030.
- Björklund, A., Finnveden, G., Roth, L., 2011. Application of LCA in waste management. In: Christensen, T.H. (Eds.), Solid Waste Technology and Management, vol. 1. Wiley, Chichester, UK.
- Boldrin, A., Andersen, J., Moller, J., Christensen, T., Favoino, E., 2009. Composting and compost utilization: Accounting of greenhouse gases and global warming contributions. Waste. Manage. Res. 27(8), 800-812.

– B
oldrin, A., Neidel, T. L., Damgaard, A., Bhander, G. S., Møller, J., Christensen, T. H., 2011. Modelling of environmental impacts from biological treatment of organic municipal waste in EASEWASTE. Waste. Manage. 31(4), 619–30.

– B
uratti, C., Barbanera, M., Testarmata, F., Fantozzi, F., 2015. Life Cycle Assessment of organic waste management strategies: An Italian case study. J. Clean. Prod. 89, 125-136.

– C
hen, T., Lin C., 2008. Greenhouse gases emissions from waste management practices using Life Cycle Inventory Model. J. Hazard. Mater. 155, 23–31.

– C
hristensen, T.H., Gentil, E.C., Boldrin, A., Larsen, A.W., Weidema, B.P., Hauschild, M.Z., 2009. C balance, carbon dioxide emissions and global warming potentials in LCA-modelling of waste management systems. Waste. Manage. Res. 27, 707–715.

– C
lavreul, J., Baumeister, H., Christensen, T. H., Damgaard, A., 2014. An environmental assessment system for environmental technologies. Environ. Model. Softw. 60, 18-30.

– C
leary, J., 2010. Life cycle assessments of municipal solid waste management systems: A comparative analysis of selected peer-reviewed literature. Environ. Int. 35, 1256.

– D
el Borghi, A., Gallo, M., Del Borghi, M., 2009. A survey of life cycle approaches in waste management. Int. J. Life. Cycle. Assess. 14, 597–610.

– D
evkota, R. P., Cockfield, G., Maraseni, T. N., Bhattarai, R., Devkota, B., 2012. Assessment of Gases Emission from the Operation of the Semi-Aerobic Landfill Site by Solid Waste of Kathmandu Valley, Nepal. Environ. Res. J. 6(3), 182-186.

– D
i Maria, F., Micale, C., Contini, S., 2016. A novel approach for uncertainty propagation applied to two different bio-waste management options. Int. J. Life Cycle Assess. 21(10), 1529-1537.

– D
iaz, R., & Warith, M., 2006. Life-cycle assessment of municipal solid wastes: Development of the WASTED model. Waste. Manage. 26(8), 886-901.

– E
nvironmental Protection Agency (EPA), 2006. Solid waste management and greenhouse gases: A life-cycle assessment of emissions and sinks, Third ed. US Environmental Protection Agency, Washington, DC.

– E
PA /ICF, 2012. Documentation for Greenhouse Gas Emission and Energy Factors Used in the Waste Reduction Model (WARM) (WARM V. 12). U.S. EPA Office of Resource Conservation and Recovery, Washington DC.

– E
PA /ICF, 2016. Documentation for Greenhouse Gas Emission and Energy Factors Used in the Waste Reduction Model (WARM): Background Chapters (WARM V. 14). U.S. EPA Office of Resource Conservation and Recovery, Washington DC.

– E
PE, 2013. Protocol for the quantification of GHG emissions from waste management activities. Report by Entreprises pour l'Environnemnent, Nanterre Cedex, France.

– E
PIC and CSR (Environment and Plastics Industry Council and Corporations Supporting Recycling), 2004. Integrated waste management model for municipalities. Microsoft Excel Model, University of Waterloo,

– E
riksson, O., Bisaillon, M., 2011. Multiple system modeling of waste management. Waste. Manage. 31(12), 2620–2630.

– E
riksson, O., Olofsson, M., Ekvall, T., 2003. How model-based systems analysis can be improved for waste management planning. Waste. Manage. Res. 21, 488–500.

– E
vangelisti, S., Tagliaferri, C., Clift, R., Lettieri, P., Taylor, R., Chapman, C., 2015. Life cycle assessment of

conventional and two-stage advanced energy-from-waste technologies for municipal solid waste treatment. J. Clean. Prod. 100, 212-223.

– Fernandez-Nava, Y., del Río, J., Rodríguez-Iglesias, J., Castrillon, L., Maranon, E., 2014. Life cycle assessment of different municipal solid waste management options: a case study of Asturias (Spain). J. Clean. Prod. 81, 178-189.

– Friedrich, E., Trois, C., 2011. Quantification of greenhouse gas emissions from waste management processes for municipalities- A comparative review focusing on Africa. Waste. Manage. 31, 1585 – 1596.

– Friedrich, E., Trois, C., 2013. GHG emission factors developed for the collection. Transport and Landfilling of Municipal Waste in South African Municipalities. Waste. Manage. 33(4), 1013–1026.

– Friedrich, E., Trois, C., 2016. Current and future greenhouse gas (GHG) emissions from the management of municipal solid waste in the eThekwini Municipality – South Africa. J. Clean. Prod. 112, 4071-4083.

– Gentil, E., Christensen, T.H., Aoustin, E., 2009. Greenhouse gas accounting and waste management. Waste. Manage. Res. 27, 696–706.

– Gentil, E.C., Damgaard, A., Hauschild, M., Finnveden, G., Eriksson, O., Thorneloe, S., Kaplan, P.O., Barlaz, M., Muller, O., Matsui, Y., Ii, R., Christensen, T.H., 2010. Models for waste life cycle assessment: review of technical assumptions. Waste. Manage. 2636–2648.

– Hanandeh, A., El Zein A., 2010. Life cycle assessment of municipal solid waste management alternatives with consideration of uncertainty: SIWMS development and application. Waste. Manage. 30, 902 – 911.

– Herva, M., Neto, B., Roca, E., 2014. Environmental assessment of the integrated municipal solid waste management system in Porto (Portugal). J. Clean. Prod. 70, 183-193.

– International Energy Agency (IEA), 2014. CO2 Emissions from fuel combustion: Highlight.: From International Energy Agency, Paris. http://www.iea.org/publications/free_new_Desc.asp?PUBS_ID=2143 (accessed 06.06.17).

– IPCC, 1995. B.8 Global Warming Potential (GWP): in IPCC Second Assessment Report (SAR) - Climate Change 1995. From IPCC, Publications (1995). http://www.ipcc.ch/ipccreports/sar/wg_I/ipcc_sar_wg_I_full_report.pdf (accessed 02.01.13).

– IPCC, 1996. Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories, Module 6–Waste. Intergovernmental Panel on Climate Change, Geneva, Switzerland.

– IPCC, 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, in: Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T., Tanabe, K. (Eds.), National Greenhouse Gas Inventories Programme, IGES, Japan.

– IPCC, 2014. Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, in: Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., Kriemann, B., Savolainen, J., Schlömer, S., von Stechow, C., Zwickel, T., J.C., Minx (Eds.), Cambridge University Press, Cambridge and New York.

– ISO (International Organization for Standardization), 2006a. Environmental Management- Life Cycle Assessment - Principles and Framework. Standard ISO 14040. Geneva, Switzerland.

– ISO (International Organization for Standardization), 2006b. Environmental Management - Life Cycle Assessment - requirements and guidelines. Standard ISO 14044. Geneva, Switzerland.

– ISWA (International Solid Waste Association), 2009. Waste and climate change, ISWA White Paper. https://www.iswa.org/fileadmin/ user_upload/_temp_/WEB_ISWA_White_paper.pdf (accessed 01.05.18).

– Itoiz, E., Gasol, C., Farreny, R., Rieradevall, J., Gabarrell, X., 2013. CO2ZW: Carbon footprint tool for municipal solid waste management for policy options in Europe. Inventory of Mediterranean countries. Energy. Policy. 623-632.

– Kahn, Ribeiro, S., Kobayashi, S., Beuthe, M., Gasca, J., Greene, D., Lee, D. S., Muromachi, Y., Newton, P. J., Plotkin, S., Sperling, D., Wit, R., Zhou, P. J., 2007. Transport and its infrastructure. In Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, in: Metz, B., Davidson, O.R., Bosch, P.R., Dave, R., Meyer, L.A. (Eds), Cambridge University Press, Cambridge.

– Karmperis, A. C., Aravossis, K., Tatsiopoulos, I. P., Sotirchos, A., 2013. Decision support models for solid waste management: Review and game-theoretic approaches. Waste. Manage. 33(5), 1290-1301.

– Kulczycka, J., Łelek, L., Lewandowska,A., Zarebska, J., 2015. Life Cycle Assessment of Municipal Solid Waste Management – Comparison of Results Using Different LCA Models. Pol. J. Environ. Stud. 24, 125-140.

– Laceco-Ramboll, 2012. Preparation of Pre-qualification documents and Tender Documents for Solid Waste Management in Lebanon, Sub Report 1, Baseline Study. CDR, Beirut.

– Larsen, A.W., Vrgoc, M., Christensen, T.H., Lieberknecht, P., 2009. Diesel consumption in waste collection and transport and its environmental significance. Waste. Manage. Res. 27, 652–659.

– Levis, J.W., Barlaz, M.A., DeCarolis, J.F., Ranjithan, S.R., 2013. A generalized multistage optimization modeling framework for life-cycle assessment-based integrated solid waste management. Environ. Model. Softw. 50, 51–65.

– Liu, Y., Ni, Z., Kong, X., Liu, J., 2017. Greenhouse gas emissions from municipal solid waste with a high organic fraction under different management scenarios. J. Clean. Prod. 147, 451-457.

– Laurent, A., Clavreul, J., Bernstad, A., Bakas, I., Niero, M., Gentil, E., Hauschild, M. Z., 2014. Review of LCA studies of solid waste management systems – Part II: Methodological guidance for a better practice. Waste. Manage. 34(3), 589-606.

– Maalouf, A., El-Fadel, M., 2018. Carbon footprint of integrated waste management systems with implications of food waste diversion into the wastewater stream. Resour. Conserv. Recy. 133, 263-277.

– MacDonald, M.L., 1996. Solid waste management models: A state of the art review. J. Solid. Waste. Technol. Manage. 23(2):73–83.

– Manfredi, S., Tonini, D., Christensen, T.H., Scharff, H., 2009. Landfilling of waste: accounting of greenhouse gases and global warming contributions. Waste. Manage. Res. 27, 825–836.

– Maraseni, T. N., Maroulis, J., 2008. Piggery: From environmental pollution to a climate change solution. J. Environ. Sci. Health 43(4), 358-363.

– Maraseni, T. N., Chen, G., Guangren, Q., 2010. Towards a faster and broader application of biochar: Appropriate marketing mechanisms. Int. J. Environ. Studies 67(6), 851-860.

– Marchi, M., Pulselli, F.M., Mangiavacchi, S., Menghetti, F., Marchettini, N., Bastianoni, S., 2017. The greenhouse gas inventory as a tool for planning Integrated Waste Management Systems: a case study in central Italy. J. Clean. Prod. 142, 351-359.

– McDougall, F., White, P., Franke, M., and Hindle, P., 2001. Integrated Solid Waste Management: A Life cycle Inventory, second ed. Blackwell Science, Oxford.

– Merrild, H., Damgaard, A., Christensen, T.H., 2009. Recycling of paper: accounting of greenhouse gases and global warming contributions. Waste. Manage. Res. 27,746–753.

– MoE/UNDP/GEF, 2015. National Greenhouse Gas Inventory Report and Mitigation Analysis for the Waste Sector in

Lebanon. MoE/UNDP/GEF, Beirut.

- Mohareb, A. K., Warith, M. A., Diaz, R., 2008. Modelling greenhouse gas emissions for municipal solid waste management strategies in Ottawa, Ontario, Canada. Resour. Conserv. Recy. 52 (11), 1241-1251.
- Mohareb, E., Maclean, H., Kennedy, C., 2011. Greenhouse Gas Emissions from Waste Management—Assessment of Quantification Methods. JAPCA. J. Air. Waste. Ma. 480-493.
- Møller, J., Boldrin, A., Christensen, T. H., 2009. Anaerobic digestion and digestate use: accounting of greenhouse gases and global warming contribution. Waste. Manage. Res. 27(8), 813–24.
- Morrissey, A.J., Browne, J., 2004. Waste management models and their application to sustainable waste management. Waste. Manage. 24 (3), 297–308.
- Nabavi-Pelesaraei, A., Bayat, R., Hosseinzadeh-Bandbafha, H., Afrasyabi, H., Chau, K., 2017. Modeling of energy consumption and environmental life cycle assessment for incineration and landfill systems of municipal solid waste management - A case study in Tehran Metropolis of Iran. J. Clean. Prod. 148, 427-440.
- Othman, S.N., Noor, Z.Z., Abba, A.H., Yusuf, R.O., Abu Hassan, M.A., 2013. Review of life cycle assessment of integrated solid waste management in some Asian countries. J. Clean. Prod. 41, 251-262.
- Pires, A., Martinho, G., Chang, N., 2011. Solid Waste Management in European countries: a review of systems analysis techniques. J. Environ. Manage. 92, 1033 - 1050.
- Quiros, R., Gabarrell, X., Villalba, G., Barrena, R., García, A., Torrente, J., Font, X., 2015. The application of LCA to alternative methods for treating the organic fiber produced from autoclaving unsorted municipal solid waste: case study of Catalonia. J. Clean. Prod. 107, 516-528.
- Rigamonti, L., Grosso, M., Giugliano, M., 2010. Life cycle assessment of sub-units composing a MSW management system. J. Clean. Prod. 18, 1652-1662. http:// dx.doi.org/10.1016/j.jclepro.2010.06.029.
- Rimaityté, I., Denafas, G., Jager, J., 2007. Report: environmental assessment of Darmstadt (Germany) municipal waste incineration plant. Waste. Manage. Res. 25, 177–182.
- Ripa, M., Fiorentino, G., Vacca, V., Ulgiati, S., 2017. The relevance of site-specific data in Life Cycle Assessment (LCA). The case of the municipal solid waste management in the metropolitan city of Naples (Italy). J. Clean. Prod. 142, 445-460.
- Rossi, V., Cleeve-Edwards, N., Lundquist, L., Schenker, U., Dubois, C., Humbert, S., Jolliet, O., 2015. Life cycle assessment of end-of-life options for two biodegradable packaging materials: sound application of the European waste hierarchy. J. Clean. Prod. 86, 132-145.
- Smith, A., Brown, K., Ogilivie, S., 2001. Waste Management Options and Climate Change, European Commission Luxembourg.
- Spokas, K., Bogner, J., Corcoran, M., Walker, S., 2015. From California dreaming to California data: Challenging historic models for landfill CH_4 emissions. Elementa: Science of the Anthropocene.
- Tascione, V., Mosca, R., Raggi, A., 2016. Optimizing the environmental performance of integrated waste management scenarios by means of linear programming: a case study. J. Clean. Prod. 112, 3086-3096.
- Thomsen, M., Seghetta, M., Mikkelsen, M.H., Gyldenkærne, S., Becker, T., Caro, D., Frederiksen, P., 2017. Comparative life cycle assessment of biowaste to resource management systems - A Danish case study. J. Clean. Prod. 142, 4050-4058.
- UNFCCC (United Nations Framework Convention on Climate Change), 2015. Adoption of the Paris agreement. https://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf (accessed 10.01.17).

- Vergara, S. E., Damgaard, A., Horvathc, A., 2011. Boundaries matter: Greenhouse gas emission reductions from alternative waste treatment strategies for California’s municipal solid waste. Resour. Conserv. Recy. 87-97.
- Winkler, J., Bilitewski, B., 2007. Comparative evaluation of life cycle assessment models for solid waste management. Waste. Manage. 27 (8), 1021–1031.
- Yay, A. S., 2015. Application of life cycle assessment (LCA) for municipal solid waste management: a case study of Sakarya. J. Clean. Prod. 94, 284-293.

Highlights

- Accounting methods for aggregated and disaggregated emissions from waste were compared
- Aggregated variability dropped from 3-65% to 2-17% when default parameters were standardized
- Disaggregated variability reached several folds by source or gas
- Variability can affect commitments under the UNFCCC or investments in carbon credit
- A framework is proposed to minimize variability under developed and developing economies